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Satellite Power System
Concept Development and Evaluation Program

Volume II
System Definition

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I. SUMMARY

A. SYSTEM REQUIREMENTS AND GUIDELINES

Any optimal new source of energy should satisfy several requirements. It should be nondepletable with a large positive energy payback over its useful life, be capable of baseload operation, and have no fundamental constraint on capacity. It should be compatible with power grids, economically competitive, and environmentally acceptable. It snould not make excessive use of critical resources and should be capable of development with reasonable cost, time, and risk.

Based on these general requirements and on preliminary studies of the solar power satellite (SPS) concept that defined some constraints on system size (ref. 1), some specific guidelines were developed for the reference system definition effort. They should not be taken as firm requirements for future studies. The most significant of these guidelines are as follows.

1. Each satellite system shall be capable of delivering 5 gigawatts to the power grid.

2. The nominal lifetime of the satellites and ground stations shall be 30 years.

3. Satellites shall be in geosynchronous orbit (GEO), with power transmission by microwave at 2.45 gigahertz.

4. The construction rate shall be 10 gigawatts per year for 30 years.

5. The maximum microwave power density in the ionosphere shall be 23 mW/cm^2.

6. Only terrestrial materials shall be used.

B. REFERENCE SYSTEM

The definition of a reference system was undertaken primarily to provide a standardized point of departure for technical, environmental, societal, and comparative assessment activities. This definition was approached with the basic idea that a reasonably high degree of certainty should be associated with the feasibility of the program within the assumed schedule. This meant that, although substantial technological advances would undoubtedly be necessary, major breakthroughs should not be involved. Earlier work (e.g., ref. 1) had indicated that such an approach could yield a competitive system. Any subsequent advances that were not contemplated in the reference system would, of course, only enhance the competitive position of the SPS concept.

The reference SPS consists basically of a photovoltaic solar energy conversion system approximately 5 by 10 kilometers, a 1-kilometer-diameter planar microwave transmitting antenna, and a ground receiving station approximately 10 by 13 kilometers. Each system provides 5 gigawatts of electrical power to the utility grid. There are two versions of the solar energy conversion system: silicon (Si) cells without solar concentration (CR1) and gallium arsenide (GaAs) solar cells with a geometric concentration ratio of 2 (CR2). The satellite is constructed in synchronous orbit. The general arrangements are illustrated in figure I-1. Characteristics of the reference system are given in table I-1, and the reference system is described in detail in reference 2.

Several alternative systems were considered during the definition of the reference system. These are discussed in the following sections.

1. ENERGY CONVERSION AND POWER MANAGEMENT

Several power generation options were considered, including silicon, gallium arsenide, and thin-film photovoltaics; solar/Brayton and solar/Rankine cycle thermal engines; and solar/thermionic and nuclear/Brayton systems (refs. 3b and 4). Of these, the last two were rejected early because of large mass penalties relative to the other systems. The helium Brayton and potassium Rankine systems are nearly competitive with the photovoltaic options in mass and cost, but the Brayton cycle achieves competitive mass only at very high turbine inlet temperatures; the materials technology was thought to be insufficiently defined to consider the Brayton cycle as a reference system. The Rankine cycle is an alternative to the photovoltaic systems, either with potassium as the working fluid (ref. 5c) or in a dual-cycle mode with cesium and steam (ref. 4b). These appear competitive with photovoltaics but were not selected as the reference system because of turbomachinery and radiator maintenance questions and the difficulty of construction relative to the photovoltaics.

Various thin-film photovoltaic systems have been considered (refs. 5c and 6), including GaAs, cadmium sulfide (CdS), indium phosphide (InP), copper indium selenide (CuInSe), and others. The principal problem is, except for GaAs, demonstration of competitive efficiencies. Since the technology of most of these materials is relatively new, substantial advances are possible. To minimize technological uncertainty while at the same time considering the potential advantages of a thin-film system, both silicon and gallium arsenide were adopted for the reference system.

A sunlight concentration ratio of 2 reduces the cost and weight of a gallium arsenide system but is not effective for silicon (ref. 3b). Gallium arsenide at CR2 is substantially lighter than silicon at CR1 but presents technological and cost problems. Pending resolution of these questions, both systems were retained in the reference system.

A geostationary orbit, with zero eccentricity and inclination, provides continuous power transmission and permits uniform (unaccelerated) motion of the transmitting antenna. Geosynchronous orbits with small inclinations and/or eccentricities offer possibilities of reduced shadowing of one satellite by another and of several satellites sharing a single synchronous orbit slot. These possibilities have not been evaluated in detail.

The satellite is oriented toward the Sun but with the rotary joint axis always perpendicular to the orbit plane (POP). This attitude minimizes the gravity-gradient torque but results in an average loss of 4 percent of the incident solar energy from solar declination variations during the year (ref. 1).

Solar radiation pressure is the dominant perturbative force, requiring on the order of 50 tonnes of propellant per year if accentricity is to be held at zero. By differential thrusting, this orbitkeeping impulse can be applied to attitude control, which would otherwise require nearly as much propellant itself. It also appears possible to depart from the POP orientation by several degrees without additional propellant expenditure and, thereby, to reduce solar energy losses (ref. 7).

The two reference configurations are illustrated in figure I-1. The structure is fabricated in geosynchronous orbit using graphite-fiber-reinforced thermoplastic for minimum thermal expansion. The estimated mass of the energy conversion system including growth margin is 17 000 tonnes for gallium arsenide (CR2) and 34 000 tonnes for silicon (CR1).

2. MICROWAVE POWER TRANSMISSION AND RECEPTION

The size of the system is constrained by the characteristics and limitations of the microwave power transmission system (MPTS). A reference set of efficiencies has been defined (ref. 2) that represents reasonable goals for each step in the power conversion-transmission-reception chain (fig. I-2). Because of thermal limitations on antenna materials, these efficiencies permit a peak microwave power density of 22 kW/m^2 at the transmitter. This limit, together with a limit of 23 mW/cm^2 at the ionosphere and the reference antenna taper, leads to a maximum power of 5 gigawatts per microwave link delivered to the power grid (ref. 1). This is the value selected for the reference system. There is recent evidence that 23 mW/cm^2 may be conservative (ref. 8); if so, the maximum power per link could be increased.

The microwave power transmission system is the same for both configurations (i.e., silicon and gallium arsenide). The mass of the reference MPTS is 17 000 tonnes, including margin.

For radiofrequency (rf) generation, the klystron was selected over the amplitron because of higher gain, lower noise, and higher output per tube. The magnetron appears promising but has not been examined as thoroughly as the klystron and the amplitron. Solid-state rf generators offer several advantages; they are discussed in the next section. A slotted waveguide array is the preferred type of radiating element based on high efficiency and simplicity. The waveguides are assembled into 10- by 10-meter subarrays; this size represents a compromise between the active mechanical alinement required for larger subarrays and the greater phase control complexity of smaller subarrays.

A wide variety of transmitter power density tapers has been studied (ref. 9). A 10-step, 10-decibel Gaussian taper has been selected for the reference system as a good compromise among peak power density, side-lobe levels, and mechanical complexity. The reference system employs a retrodirective phase control system, although ground command and hybrid systems are promising alternatives.

The ground receiving station, or rectenna, is elliptical. The active area is 10 by 13.2 kilometers at 35° latitude, plus a buffer zone to keep the microwave radiation exposure of the public below 0.1 mW/cm^2. The rectenna consists of half-wave dipole receiving elements and Schottky barrier diodes on panels normal to the microwave beam, with power distribution and conditioning equipment for the required interfaces with the power grid.

3. SPACE CONSTRUCTION

A major consideration in the selection of the reference configuration was ease of construction. The scale of the program mandates the highest possible degree of automation in the construction process (the alternative would be an on-orbit work force of many thousands); this in turn places a premium on highly regular configurations that can be constructed with a small number of frequently repeated operations. Ease of construction was, for example, one consideration in the selection of an end-mounted rather than a central antenna. The repeatability of the photovoltaic configurations gave them a constructability advantage over the thermal systems, which require a relatively large number of different construction operations.

The reference system is constructed in synchronous orbit using material transported from low Earth orbit (LEO) (fig. I-3). The construction base is permanently manned by a crew of approximately 400 for construction, plus several hundred for maintenance of operating satellites. Construction in low orbit of sections of the satellite with subsequent self-powered transfer to synchronous orbit for assembly is an alternate approach, if radiation damage to the solar cells used for transfer can be annealed or otherwise reversed.

4. SPACE TRANSPORTATION

Transportation to low orbit is accomplished by a two-stage winged heavy-lift launch vehicle (HLLV) with a payload of 420 tonnes. A ballistic HLLV was also considered, but ocean recovery introduces operational complexities and the winged HLLV can also be used for personnel transport, eliminating the need for development of a personnel launch vehicle. From the low-orbit staging base (fig. I-3), electric orbital transfer vehicles (EOTV's) transport 4000 tonnes of cargo per flight (one launch every 11 days) to synchronous orbit. Radiation damage to the EOTV solar cells during the long passage through the Earth's trapped radiation belts will be severe, but the EOTV offers a substantial cost saving relative to chemical propulsion. Chemical rockets are used to transfer personnel to minimize travel and radiation exposure times.

C. ALTERNATE CONCEPTS

1. POWER LEVEL AND TRANSMISSION FREQUENCY

The large amount of power per microwave link and the large land area required by the rectenna are sometimes mentioned as disadvantages of the

SPS reference systems. These parameters arose from natural constraints on the system (described previously) and from a desire to minimize the cost of energy, which can be achieved by, among other things, economies of scale.

Sensitivity analyses (refs. 10 and 11) have shown that, although maximizing output per microwave link does in fact minimize energy cost, output per link can be reduced to approximately 2.5 to 3 gigawatts without excessive increase in the cost per kilowatthour. The rectenna area for the smaller system is approximately half that of the reference system; rectenna siting is accordingly less constrained.

Rectenna size can also be reduced by use of a higher transmission frequency. An industrial band at 5.8 gigahertz is potentially usable and has been investigated (ref. 11). Ionospheric heating is not a constraint at the higher frequency because of the frequency-dependent nature of the effect, but antenna heat rejection does limit the configuration. Transmission at 5.8 gigahertz is satisfactory through a dry atmosphere but degrades severely in rainy conditions; the impact of such degradation on the power grid is not known. A reasonable 5.8-gigahertz system was derived that delivered 2.7 gigawatts to the grid with a 0.75-kilometer-diameter antenna and a 5.8-kilometer-diameter rectenna. The cost was estimated at 36 percent more than the reference system per kilowatt.

2. SOLID-STATE AMPLIFIERS AND "SANDWICH" CONCEPT

The klystron microwave generators in the reference system dominate the anticipated maintenance requirements of the SPS (ref. 12b). Since solid-state components typically have much higher mean times between failures than conventional electronic tubes, their use in the MPTS could greatly reduce maintenance time and personnel. They also offer the potential for mass production as part of an integrated circuit.

One approach is to replace the reference end-mounted antenna with a solid-state version. Because solid-state devices require a lower operating temperature than the klystron, the optimum solid-state system has a larger transmitting antenna, a smaller rectenna, and lower total power output; for the reference taper and efficiency chain, typical values are 1.4 kilometers, 7 kilometers, and 2.5 gigawatts, respectively (ref. 12b). Because of the low voltages required by solid-state devices, the power distribution system must pay a substantial mass penalty (thousands of tons), either in conductors or in dc-dc conversion equipment.

The power distribution system can be virtually eliminated by the "sandwich" concept (ref. 7), in which solar cells are mounted on one side of a substrate and the solid-state power amplifiers on the other, with direct electrical power connections between small groups of cells and amplifiers. To illuminate the solar array while the antenna points continuously at the ground, a system of reflectors is used. By using multiple reflecting paths, concentration can be achieved. Figure I-4 shows one proposed configuration that delivers 1.2 gigawatts to each of two rectenna sites.

One major disadvantage of the sandwich concept is the difficulty in tapering the transmitter power density for side-lobe suppression without reintroducing power distribution penalties. Consequently, uniform illumination is used. A second major disadvantage is that the output power from the rectenna is about one-fifth of that from the reference system. The rectenna land areas are the same because of the uniform illumination taper. A 10- by 13-kilometer perimeter is necessary to contain illumination levels above 0.1 mW/cm^2 with the system shown in figure I-4.

3. LASERS

Lasers have been suggested as an alternative to microwaves for power transmission. Several significant advantages and disadvantages of lasers have been identified (refs. 13 and 14). Some of the advantages over a microwave system are as follows.

a. Much less land is required for receiving sites.

b. Radiation levels outside the receiving site are negligible.

c. There is no interference by side lobes with communications or other electromagnetic systems.

d. The power per receiver can be much lower.

e. A small-scale demonstration is feasible.

Some disadvantages are the following.

a. Attenuation by clouds appears to be a serious problem.

b. Thermal blooming may be a problem at very high intensities.

c. Clouds may be induced above the receiving station.

d. A laser SPS may be perceived as a potential weapon.

e. High-power laser technology is less developed than microwave technology.

Some of these disadvantages could rule out the laser concept and require thorough evaluation.

A laser SPS concept has been described in some detail (ref. 14), consisting of power satellites in Sun-synchronous orbits and relay satellites at GEO. Carbon dioxide (CO_2) electric discharge lasers (EDL's) are used for power transmission. Some questionable aspects of the concept are the high efficiency of the energy conversion system, the reliability of the EDL, and the dependability of the energy exchanger.

Three types of laser that may be applicable to the SPS have received primary emphasis in recent comparative studies (ref. 15). Although

EDL technology is well established, solar energy must first be converted to electricity. An indirect solar-pumped laser (IOPL) can avoid the sunlight-to-electricity conversion, but feasibility has not been demonstrated. The free-electron laser (FEL) is potentially efficient and does not require a lasant material; feasibility has not been established. Other types that appeared uncompetitive in a preliminary screening include gas dynamic, chemical, and direct solar-pumped lasers. Figure I-5 shows the mass in orbit of the laser options studied. All are heavier per delivered kilowatt than the reference microwave system. The best (FEL) is within a factor of 2 in mass and cost per kilowatt. The FEL and the indirect solar-pumped laser offer the most promise for further research.

D. COSTS

The system definition studies of the SPS have led to a set of cost estimates. These costs were based on the scenario defined in the reference system report (ref. 2) and the production rates associated with that scenario. Detailed cost data may be found in references 7c, 16b, and 17.

The cost of a 5-gigawatt silicon reference system satellite, based on the average unit cost of 60 satellites, was determined to be $5 billion (1977 dollars). Space transportation - the cost of transporting the materials and personnel to construct a 5-gigawatt satellite in geosynchronous orbit - was $2.8 billion. The ground receiving station, including rf-dc conversion, power distribution and conditioning, grid interface, structure, and land acquisition, was $2.2 billion. Assembly and support during construction, based on crew salaries and resupply at LEO and GEO bases, was $840 million. Program management and integration was estimated to be $430 million. The sum of these costs is $11.3 billion for each 5-gigawatt system, or $2260/kW (fig. I-6).

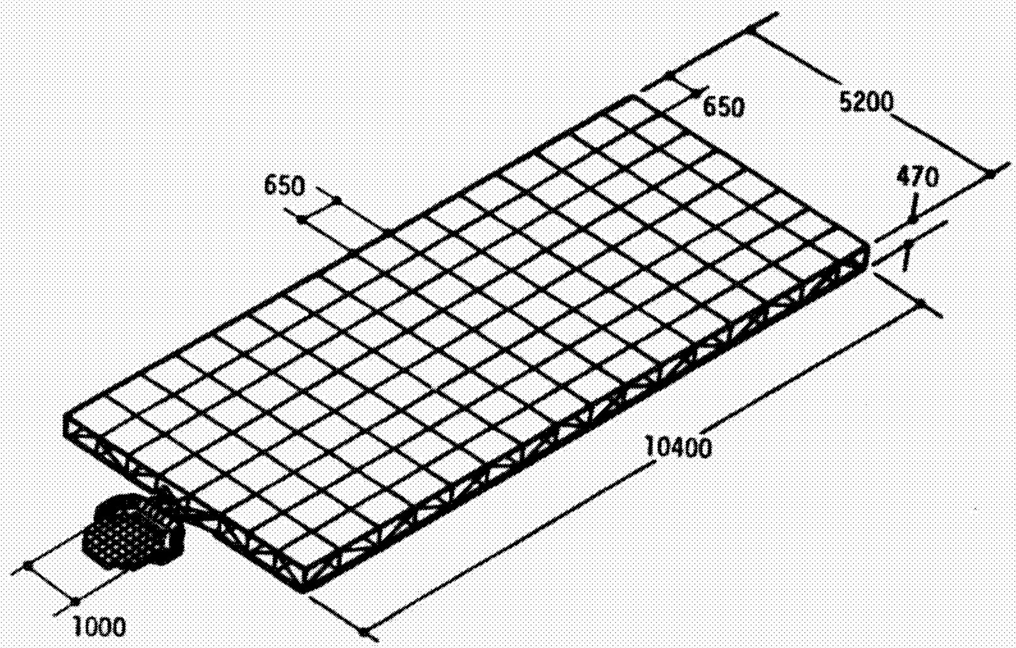
The front-end (nonrecurring) costs are defined as the cost of developing the capability to produce the hardware, launch facilities, launch fleets, and LEO and GEO bases and are estimated to be about $104 billion spread over a 20-year period. Annual maintenance costs per satellite system are estimated to be $203 million. Transportation cost represents more than half of the total; more than 80 percent of the transportation cost is for personnel and their supplies, and about 20 percent is for transportation of replacement materials. The next largest item, $39 million/yr, is replacement parts for klystrons, dc-dc converters, and other satellite components.

All the costs given previously are for the silicon reference system. The gallium arsenide reference system costs are similar. Because of its lower mass, the GaAs system transportation cost is lower. The solar cell costs, however, are higher, and the total cost per system is estimated at $13.8 billion (ref. 7c). Because of differences in cost-estimating methods, this figure is not directly comparable to the $11.3 billion given previously for the silicon system.

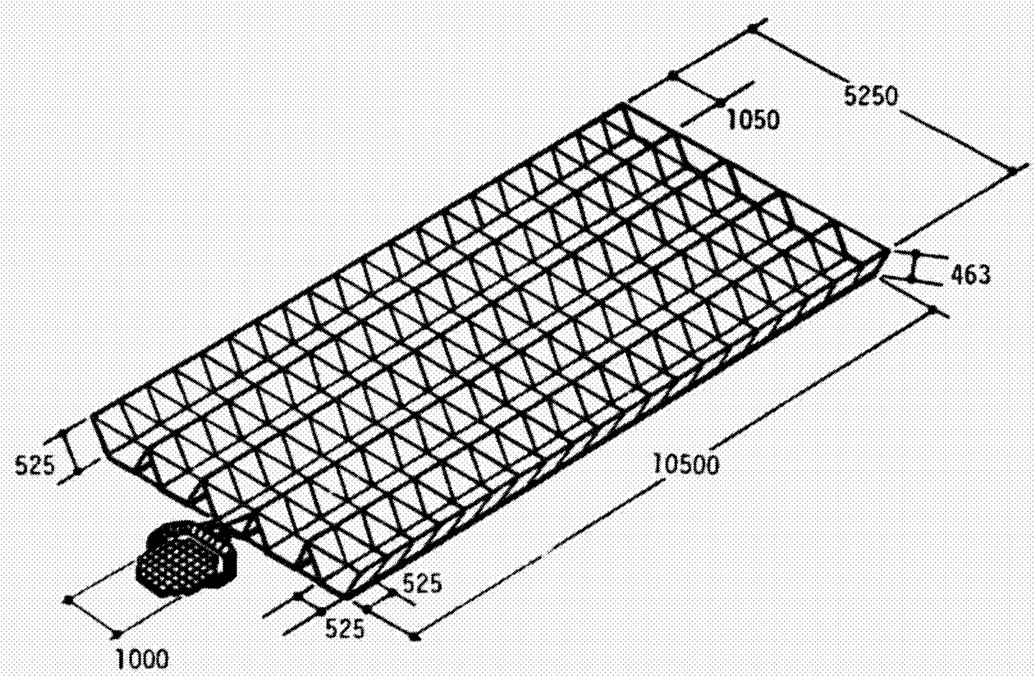
TABLE I-1.- REFERENCE SYSTEM CHARACTERISTICS

SPS generation capability,[a] GW	5
Overall dimensions, km	5.3 by 10.4
Power conversion	Photovoltaic
Satellite mass, kg	
Gallium aluminum arsenide[b]	34×10^6
Silicon[c]	51×10^6
Structure material	Graphite composite
Construction location	GEO
Transportation	
Earth to LEO[d]	
Cargo	
Vehicle	Vertical takeoff, winged 2-stage
Payload, kg	424 000
Personnel	
Vehicle	Modified Shuttle
Passengers	75
LEO to GEO	
Cargo vehicle	Dedicated EOTV[e]
Personnel	
Vehicle	2-stage LO_2/LH_2[f]
Passengers	75
Microwave power transmission	
No. of antennas	1
dc-rf[g] converter	Klystron
Frequency, GHz	2.45
Rectenna dimensions, km	10 by 13
Rectenna power density, mW/cm^2	
Center	23
Edge	1

[a]Utility interface.
[b]CR = 2.
[c]CR = 1.
[d]Low Earth orbit.
[e]Electric orbital transfer vehicle.
[f]Liquid oxygen/liquid hydrogen.
[g]Direct current to radiofrequency.



(a) Silicon (CR1).



Dimensions in meters

(b) GaAlAs (CR2).

Figure I-1.- Reference configurations.

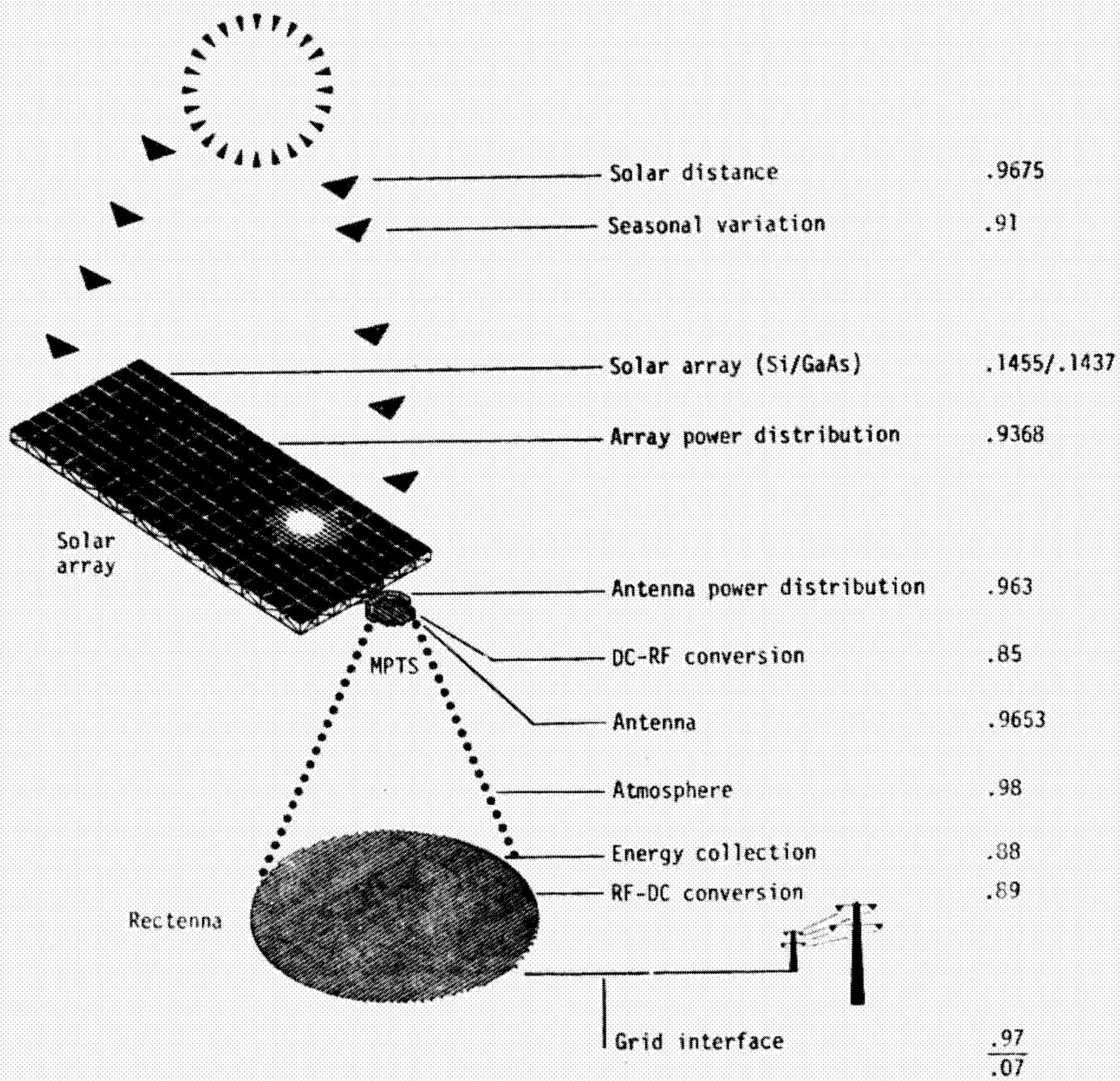


Figure I-2.- Reference efficiency chain.

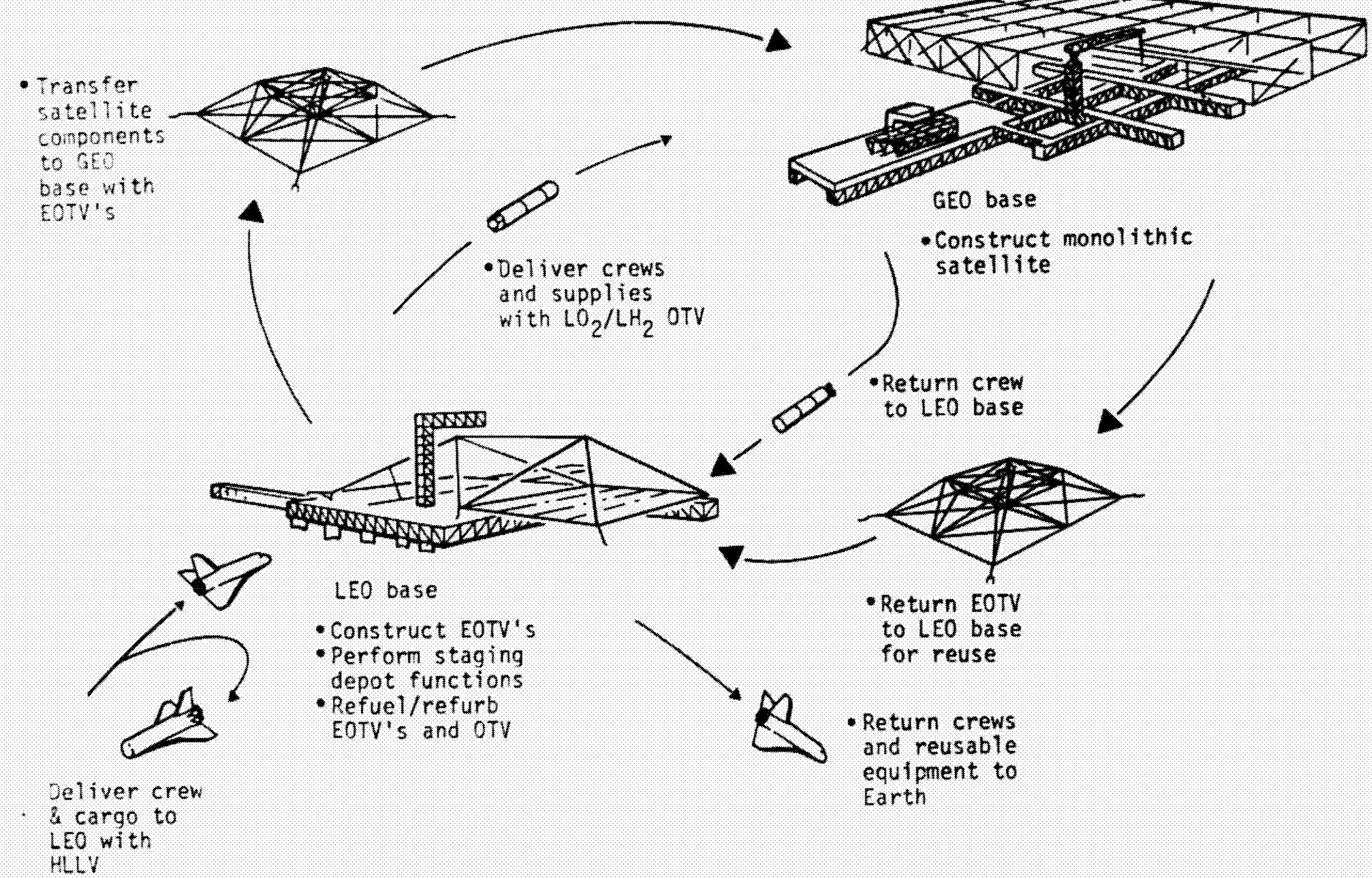


Figure I-3.- Space transportation and construction.

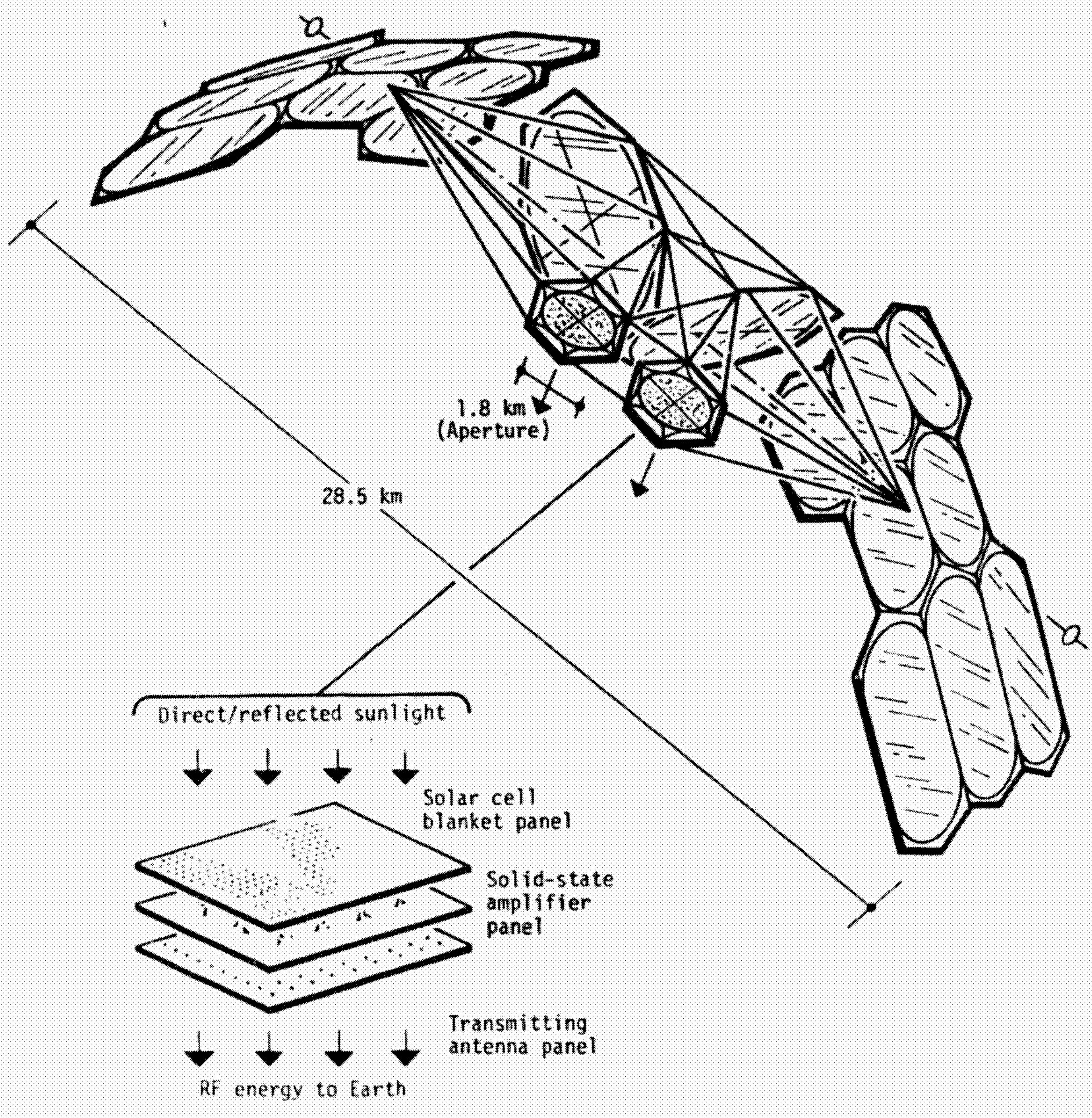


Figure I-4.- Solid-state "sandwich" concept.

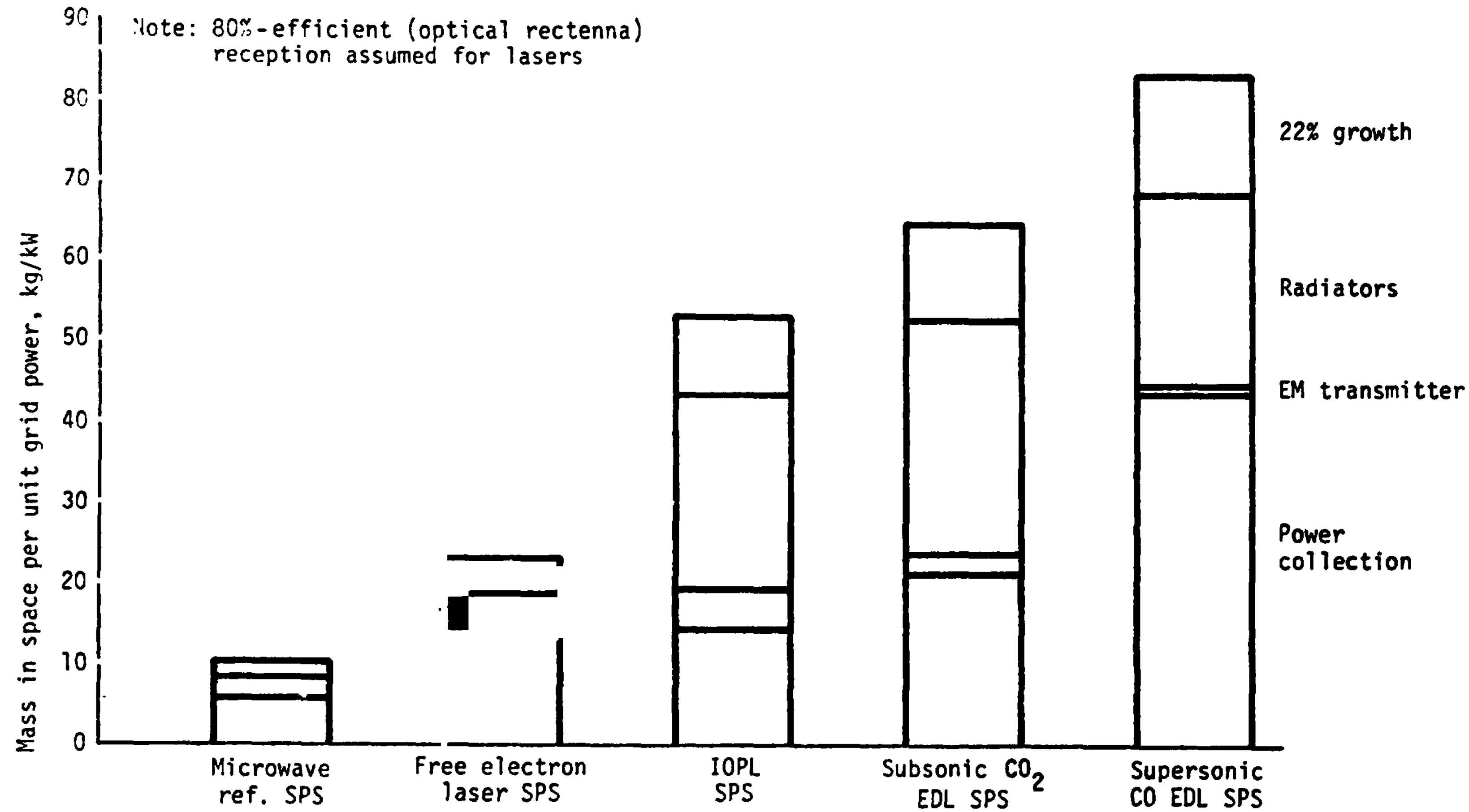
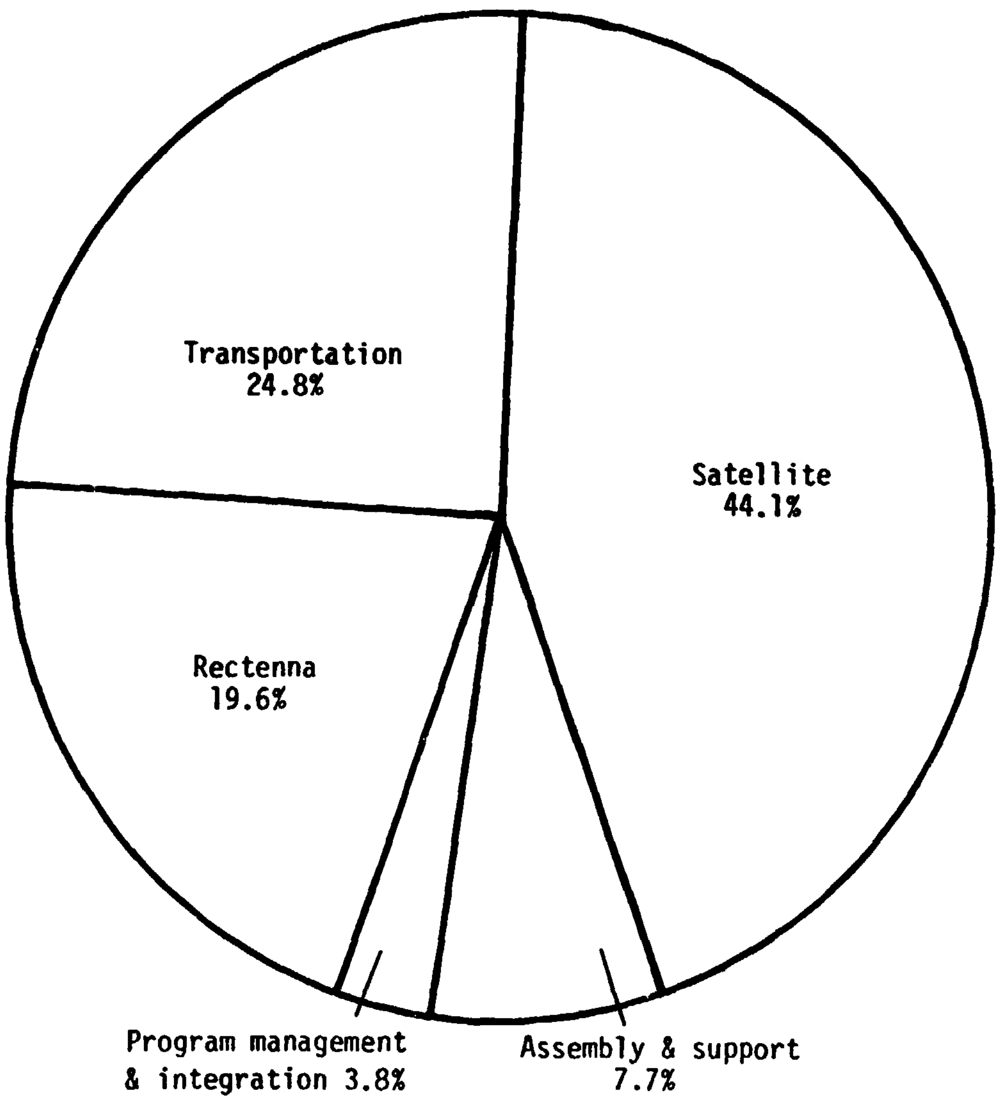


Figure I-5.- Laser SPS mass comparison.



SPS recurring cost - $11.3B/5-GW system

Figure I-6.- SPS unit cost.

II. INTRODUCTION

In the summer of 1977, the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) embarked on a joint assessment of the satellite power system concept according to the SPS Concept Development and Evaluation Program (CDEP) Plan (ref. 18). Under this plan, DOE and NASA undertook evaluation of the SPS concept in four major areas: systems definition and environmental, societal, and comparative assessments. The NASA's principal effort was in the systems definition area. This report is a summary of the results of NASA activities in systems definition. Detailed results are provided in Volumes III to VII as listed below; Volume I provides a summary of the NASA technical assessment effort.

Volume I - Technical Assessment Summary Report - NASA TM 58232

Volume III - Power Transmission and Reception - NASA RP 1076

Volume IV - Energy Conversion and Power Management - NASA TM 58237

Volume V - Structures, Controls, and Materials

Volume VI - Construction and Operations - NASA TM 58233

Volume VII - Space Transportation - NASA TM 58238

The assessment of the SPS by DOE and NASA was in response to mounting interest and controversy over the SPS concept for utilizing solar energy in a way that would overcome perceived problems of daily and weather-induced variations of sunlight received in Earth-based solar powerplants. The key to the SPS concept, as first reported in 1968 (ref. 19), is the placement of the solar energy collector and converter into space where nearly continuous illumination is received, with transmission of energy to receiving stations on Earth by means of focused beams of electromagnetic waves.

Because of various economic and technical factors, which will be discussed later in this report, SPS designs are led toward high power levels that result in space systems that have unprecedented large sizes and masses and that require levels of activity in space operations well beyond the scope foreseen in current and future plans. Nevertheless, an examination of the SPS concept by aerospace contractors, certain academic groups, and NASA led some people to the conclusion the idea had merit in that the required advances in technology could be accomplished and that the projected costs of developing and building these systems would result in delivery of baseload electrical energy in a competitive price range. Furthermore, the urgency of the energy crisis manifested in the events of 1973 and thereafter influenced studies of the SPS concept in the direction of systems and technologies that could be developed and brought to operational status as soon as possible.

The NASA began its studies of the SPS in 1972 (ref. 20). These early studies were followed by investigations at the Jet Propulsion Laboratory (JPL), particularly in the area of power transmission via microwaves (ref. 21). Intensive studies of the SPS were conducted during 1975-76 by several NASA groups (refs. 1, 9, and 22).

During 1976, a task group was formed by the Energy Research and Development Administration (ERDA), now DOE, for the purpose of reviewing the NASA SPS concepts and recommending an appropriate ERDA policy position for addressing this concept within the broader goals of the national energy research, development, and demonstration effort. This task group (ref. 23) concluded that, "considering the tremendous electric generation needs that are projected for the post-2000 period and the inherent uncertainties in the commercialization of other advanced technologies . . . , it behooves ERDA, in cooperation with NASA, to pursue some studies of the SPS concept and its potential." The findings of the ERDA task group led to the formulation of plans and scope for the joint Concept Development and Evaluation Program for making assessments of SPS.

The systems definition effort in the CDEP had these primary objectives (as modified from the CDEP plan): to evaluate the technical feasibility of the SPS concept, to define and analyze alternative system design and operational approaches, and to provide the requisite technical information for environmental, societal, and comparative assessments conducted by the Department of Energy. Table II-1 lists the major systems definition areas and the approximate funding distribution in each fiscal year (FY) of the CDEP period of performance. Included in these activities are studies and critical supporting investigations, some of which were experimental in nature, that were conducted to address key areas of SPS feasibility. Major emphasis was given to studies of systems and power transmission and reception, which are the key, unique areas of concern in the SPS.

To allow the CDEP to function in its assessment areas, it was necessary to define a version of SPS toward which all studies could be focused. This version of SPS became known as the "reference system," and it provided, to varying levels of detail, a description of all aspects of SPS, the satellite and all its subsystems, the orbital bases and equipment required to construct and maintain the satellite, all elements of a transportation system including launch sites, the ground receiving station, and the associated industrial facilities for manufacturing all required hardware (ref. 2).

The reference system was amalgamated from the results of the system definition studies of SPS, and the design choices gave emphasis to those components and subsystems that would be ready for development by 1990 in anticipation of operation of the first SPS by 2000. This emphasis restricted the range of possible options for the reference system and provided a technically plausible concept for use in the assessment process.

Because of its role in the assessment of SPS, the reference system is described briefly in Section III. Much of the system definition effort during the CDEP was spent in evaluating and expanding on the data base of the reference system, which also served as a basis for consideration of alternatives.

The cost of an energy system is, in the final analysis, the key to its acceptability. Inherent in the early studies by NASA and others were estimates of the costs of the energy delivered by SPS. Not only were these cost estimates useful in judging whether SPS could be viable, they also served in evaluating the importance and worth of various design options and operational concepts. A summary of cost estimates for a reference SPS concept has been reported (ref. 17); these are also reviewed in Section IV.

Section III contains summary discussions in the areas of energy conversion and power management; microwave power transmission and reception; construction and operations; space transportation; and crew considerations. The primary thrust of the discussion is to present study findings and unresolved issues and to describe the manner in which these factors affect the SPS concept. The basic information for the previously mentioned sections is drawn primarily from reports issued by Boeing Aerospace Company under contract to the NASA Lyndon B. Johnson Space Center (JSC) (refs. 3, 5, 10, 12, and 16) and by Rockwell International under contract to the NASA George C. Marshall Space Flight Center (MSFC) (refs. 4 and 7). Considerable benefit in the assessment process was also obtained through a series of technical workshops in which expert evaluation and advice on SPS were obtained. The findings of each workshop are recorded in appropriate sections of Volumes III to VII of this report series.

Throughout this report, there are references to a Ground-Based Exploratory Development (GBED) plan. A plan for future activities in SPS was a requirement of the CDEP, and the GBED (to be published) describes one approach or option for addressing critical technology issues in SPS as defined largely through an evaluation of the reference system. The GBED plan is a program of some urgency having the goal of resolving major remaining technological questions in 5 or 6 years. Currently, the GBED plan does not represent a preferred program option for the future.

In compliance with the NASA's publication policy, the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). As an aid to the reader, the SI units are written first and the original units are written parenthetically thereafter.

TABLE II-1.- SATELLITE POWER SYSTEM CONCEPT DEVELOPMENT AND EVALUATION PROGRAM SYSTEMS ACTIVITY FUNDING[a]

[Thousands of dollars]

Activity	FY 77	FY 78	FY 79	FY 80	Total
Systems definition	715	765	235	[b]490	2205
Solar energy conversion	85	60	100	50	295
Electrical power processing and distribution	150	50	100	-	300
Power transmission and reception	735	565	[c]1240	260	[d]2800
Structures/controls and materials	200	165	285	150	800
Operations	150	225	490	50	915
Space transportation	165	170	150	100	585
Total	2200	2000	2600	1100	7900

[a]Source: reference 24.
[b]Includes $125 000 for laser SPS.
[c]Includes $400 000 for solid-state SPS.
[d]Includes $700 000 for microwave at JPL.

III. SYSTEMS DEFINITION

A. SYSTEM REQUIREMENTS AND GUIDELINES

Any major source of energy should satisfy a number of general requirements (ref. 3b).

1. It should be nondepletable.
2. There should be no limit on potential installed capacity.
3. It should be usable as a baseload system.
4. It should produce much more energy during its lifetime than is required to create and operate it.
5. It should produce power at an economically acceptable cost.
6. It should be environmentally acceptable in all respects.
7. It should not require excessive use of critical resources.
8. It should be compatible with power grids.
9. It should be capable of development with reasonable cost, time, and risk.

Although it is possible that no energy source can completely fulfill all these requirements, it appears from the work done to date that the SPS has the potential of meeting them, at least to a reasonable degree.

In addition to the general requirements outlined previously, specific guidelines were needed for the reference system definition and assessment effort. These guidelines were based on preliminary studies of the SPS concept (refs. 1, 18, and 19) that had defined reasonable values for some of the major design parameters. It must be emphasized that these guidelines are as subject to change as are any other parameters in the light of future development work; they were established solely as the starting point for the technical assessment reported in this and companion volumes. The major guidelines and the reasons for their adoption are as follows.

1. Each satellite system shall be capable of delivering 5 gigawatts to the power grid. It was found (ref. 2) that 5 gigawatts was the maximum grid power deliverable by each microwave link within a certain set of assumptions as to frequency, efficiencies, antenna taper, etc. (See Section III.B.2 for details.) It was also assumed that each satellite would have a single transmitting antenna for simplicity, although a two-antenna configuration offers some advantages.

2. The nominal lifetime of the satellites and ground stations shall be 30 years. This lifetime was adopted primarily for economic analysis compatibility with conventional powerplants, which are typically amortized over a 30-year period.

3. The satellites shall be in geosynchronous orbit. Geosynchronous orbit offers continuous transmission capability and nearly continuous solar energy collection, with few associated technical complications compared to other orbits.

4. Power transmission shall be by microwave at 2.45 gigahertz. Microwave power transmission has been demonstrated on a small scale and appears feasible. The frequency selected is in the center of an industrial, scientific, and medical (ISM) band that imposes no restriction on electromagnetic interference; it is also subject to very slight atmospheric absorption.

5. The construction rate shall be 10 gigawatts per year for 30 years. This rate appeared to be achievable with a single construction facility. (Subsequent work has verified this conclusion.) The total capacity of the system would provide a sufficient portion of the total demand to be worthwhile.

6. The maximum power density in the ionosphere shall be 23 mW/cm^2. This parameter is a major factor in the maximum capacity of the microwave link. The value chosen represented the best estimate of the maximum allowable power density available at the beginning of the assessment.

7. Only terrestrial materials shall be used. Although lunar or asteroidal materials may be advantageous, their inclusion would add a dimension to the study that could dilute the effort unnecessarily.

The guidelines were adopted for the reference system definition as a common point of departure for the numerous organizations involved in the work. They did not rule out the consideration of alternatives, as will be seen in subsequent sections of this report.

B. REFERENCE SYSTEM DESCRIPTION

The definition of a reference system was undertaken primarily to provide a standardized point of departure for technical, environmental, societal, and comparative assessment activities. This definition was approached with the basic idea that a reasonably high degree of certainty should be associated with the feasibility of the program within the assumed schedule. This meant that, although substantial technological advances would undoubtedly be necessary, major breakthroughs should not be involved. Earlier work (e.g., ref. 1) had indicated that such an approach could yield a reasonably competitive system. Any subsequent advances that were not contemplated in the reference system would, of course, only enhance the competitive position of the SPS concept.

Implicit in this approach is a high probability that the reference system will not be the optimum system; it is also unlikely to be the system that is actually built for commercial use. This situation is unavoidable because (1) insufficient time and resources were available to explore all possible options to the depth necessary to arrive at an optimum system and (2) it is certain that the developmental phase of the program will produce materials, processes, and concepts that do not yet exist but that would be of advantage in the system as finally built. Thus, not only is the reference system not the optimum, it cannot be expected to be the optimum.

This does not mean that the reference system was not optimized to the extent possible. Within the established guidelines, many alternatives were studied in considerable detail, and only the most promising in terms of technical feasibility and economic viability were selected to make up the reference system. Sections III.B and III.C of this report are devoted to discussions of these alternatives and the reasons for the selections that were made.

The reference SPS consists basically of a photovoltaic solar energy conversion system approximately 54 square kilometers in area, a 1-kilometer-diameter planar microwave transmitting antenna, and a ground receiving station approximately 10 by 13 kilometers. Each system provides 5 gigawatts of electrical power to the utility grid. There are two versions of the solar energy conversion system: silicon cells without solar concentration (CR1) and gallium arsenide solar cells with a geometric concentration ratio of 2 (CR2). The overall configurations are shown in figure I-1; table I-1 summarizes the more important system parameters. The reference system is described in detail in reference 2.

1. ENERGY CONVERSION AND POWER MANAGEMENT

The function of the SPS energy conversion system is to collect solar energy and convert the solar energy to electrical power. The power management system collects, distributes, and controls the flow of electrical power on the satellite. Satellite power system definition studies have included consideration and analysis of all known potentially viable space energy conversion concepts. The emphasis has been on solar energy collection and conversion, although early studies (ref. 25) included definition and analysis of selected nuclear reactor systems. With respect to solar energy conversion systems, both photovoltaic and thermal energy conversion methods have been studied. Photovoltaic system studies involved consideration of a large number of solar cell types. In these studies, various levels of solar concentration were investigated (refs. 3 and 4).

Thermal systems studied included both static and dynamic conversion methods. The static system investigated was thermionic conversion, whereas the dynamic (rotating machinery) systems studied included the Brayton cycle, Rankine cycle, and combined (cesium/steam) cycle concepts. Alternative working fluids, cycle temperatures, and associated performance/technology levels were analyzed and evaluated. A number of solar concentrator concepts (e.g., parabolic, faceted) with concentration ratios of 2000 and greater were investigated (refs. 3 to 5 and 7).

In the early nuclear reactor system studies (ref. 25), rotating particle bed, molten-salt breeder, and uranium hexafluoride reactor concepts in combination with Brayton, Rankine, and thermionic thermal energy conversion were investigated. The following sections contain summaries of the key results of the previously mentioned SPS energy conversion studies.

a. Energy Conversion

(1) Solar photovoltaics.- From the earliest SPS studies, solar photovoltaic technology has provided a standard of comparison for other solar collection/conversion systems. Initial NASA studies (refs. 1 and 22) emphasized the use of silicon solar cells; however, consideration was given to gallium arsenide and other, less developed solar cell types. Subsequent studies initiated during the CDEP (refs. 3 to 5, 7, 10, 12, 14, 16, 26, and 27) involved more in-depth evaluation of silicon and gallium arsenide and other cell types, including amorphous silicon, cadmium sulfide, indium cadmium sulfide, copper indium selenide, multibandgap, and optically filtered concepts.

In comparing the various photovoltaic options, the single-crystal silicon cell and the gallium aluminum arsenide (GaAlAs) cells emerged as the most promising for SPS application. Other solar cell types (listed previously) generally have the potential advantage of lower costs and/or lower mass per unit area; however, the performance (efficiency) currently is low and mass production methods have not been devised.

The SPS reference system incorporated silicon and gallium arsenide solar cells as optional energy conversion systems. An overall conceptual drawing of the silicon cell concept is illustrated in figure III-1; figure III-2 contains details of the silicon solar cell blanket construction used in the reference system. Figure III-3 is a conceptual drawing of the GaAs solar cell reference system. Figure III-4 contains details of the GaAs solar cell blanket construction.

An example comparison of the gallium arsenide and silicon cell options for a specific SPS configuration is provided in table III-1. The cost data are presented for parametric comparison only and are, therefore, not directly comparable to the reference system costs given in Section IV. Note that with solar concentration (CR = 2), the gallium arsenide system and the silicon system are competitive in terms of relative cost of hardware delivered to GEO. Because of this close competition, silicon and gallium arsenide are both viable candidates for SPS application.

The use of solar cells in SPS, whether silicon or gallium arsenide, is predicated on substantial reductions in the cost to produce multigigawatt quantities of cells. It is believed that such a cost reduction will be forthcoming over the next 5 to 15 years as a result of the DOE photovoltaic conversion program. Projections of solar cell cost and associated production quantities are shown in figure III-5. As indicated, the 1986 goal for terrestrial solar cells is $500/kW in quantities of 500 megawatts. The SPS reference scenario would require 20 000 to 30 000 MW/yr capacity in the 2000 time frame. The cost projection for the space-type cells in 2000 is

$200/kW to $400/kW. Although it is recognized that the weight and space radiation resistance requirements for space cells are different from those for terrestrial use, the $200 to $400 range appears reasonable for SPS. For comparison, present-day space cells (silicon) cost $50 000/kW to $80 000/kW with annual production rates of only a few tens of kilowatts.

The significant findings resulting from the photovoltaic energy conversion studies are as follows.

(a) Solar cells: Among the solar cell types available for consideration, single-crystal silicon cells and gallium aluminum arsenide cells have the potential of lightweight components and low-cost production to meet SPS requirements. As a result, both Si and GaAlAs are considered viable options for SPS application. Key questions or unknowns to be resolved for each cell type are summarized as follows.

[1] Silicon

[a] Fabrication and process development of thin cells with an efficiency of 17 percent

[b] Improvement of space radiation resistance to performance degradation

[c] Determination of annealing characteristics for annealing of radiation-induced performance degradation

[d] Development of process for the fabrication of lightweight solar cell blankets that are compatible with annealing temperatures and long life

[2] Gallium arsenide

[a] Development of thin-film gallium arsenide cell with an efficiency of 20 percent

[b] Determination of radiation performance degradation characteristics and development of potential annealing recovery techniques

[c] Verification of recovery of gallium in sufficient quantities and at a cost compatible with SPS requirements

[d] Development of process for the fabrication of lightweight solar cell blankets that are compatible with annealing techniques and long life

(b) Radiation performance degradation: Solar cell performance (efficiency) is degraded by exposure to space radiation in both silicon and gallium arsenide cells. Silicon solar cells may be used by initially oversizing the solar array, by adding solar arrays to maintain rated output, or by in situ annealing of the solar array through laser heating to recover performance loss. The in situ annealing approach appears to be the most cost-effective and appears to be technically feasible (refs. 12b and 12d). Based on preliminary test data (ref. 4), gallium arsenide solar cells operating at 398 K (125° C) (with CR = 2.0) may have the capability of continuous annealing of radiation damage.

(c) Solar concentrators: The use of solar concentrators with silicon solar cells is not warranted on the basis of cost and weight savings because of (1) increased cell operating temperature, resulting in cell efficiency degradation; (2) low projected cost of silicon solar array blankets; and (3) more complex space construction of concentrator systems (refs. 3 and 5). The use of solar concentrators with gallium arsenide solar cells is beneficial at a concentration ratio of 2 because (1) the solar cell area required is smaller and, therefore, system cost is reduced and (2) higher cell operating temperature caused by increased solar heat input promotes annealing of radiation-induced performance degradation on a continuous basis (ref. 4).

(2) Thermal systems.- Thermal energy conversion systems consist of means for collecting and concentrating solar energy and for the transfer of this thermal energy to a thermodynamic cycle or converter module, where work is accomplished to generate electrical power. The thermal system may be either a static converter such as thermionic and thermoelectric or a dynamic system (rotating machinery) such as Rankine and Brayton cycles. The dynamic systems use a working fluid for the transport of energy within the thermodynamic cycle. In all thermal cycle systems, residual or waste heat from the cycle must be rejected to space by a space radiator to sustain operation of the system with net power output.

Thermal cycle systems may use a nuclear reactor heat source in place of solar energy. Several nuclear reactor concepts have been investigated and are summarized herein. The system definition studies have included consideration of a large number of thermal cycle systems and components. The following list includes the thermal systems that were investigated.

(a) Solar-thermal

[1] Brayton

[2] Potassium Rankine

[3] Cesium/steam combined cycle (Rankine)

[4] Organic Rankine

[5] Thermionic (TI) (including TI/Brayton combined)

[6] Thermoelectrics

(b) Solar concentrators

[1] Parabolic (including compound parabolic concentrators)

[2] Faceted

[3] Planar (CR = 2 to 8)

[4] Inflated

(c) Nuclear-thermal reactor

[1] Rotating particle bed reactor

[2] Molten-salt breeder reactor (MSBR)

[3] Uranium hexafluoride (UF)

[4] Conversion cycles (Brayton, Rankine, thermionic)

(d) Radiator types

[1] Heat pipe

[2] Fin tube, liquid

[3] Fin tube, vapor/gas

The following paragraphs consist of discussions and conclusions relative to the thermal cycle systems investigated.

(a) Brayton cycle: The schematic diagram of a closed Brayton cycle system shown in figure III-6 illustrates the fundamental elements of the Brayton cycle SPS. The solar concentrator reflects and focuses concentrated sunlight into the cavity absorber aperture. The cavity absorber is an insulated shell with heat exchanger tubing. Helium gas flowing through this tubing is heated to the turbine inlet temperature. The hot helium expands through the turbine, doing the work of turning the compressor and the electrical generator. Residual heat in the turbine exit gas is used to preheat compressor output gas before final heating in the cavity absorber. This heat transfer is accomplished in the recuperator, which is a gas-to-gas heat exchanger. The minimum gas temperature occurs at the exit of the cooler, which is a gas-to-liquid heat exchanger interfacing the helium loop to the radiator system. Waste heat is rejected to space by a liquid-metal radiator system.

Conceptual designs of solar Brayton cycle systems were developed under NASA contract. One design was based on a 10-gigawatt ground output with two microwave power transmitters. Turbine and materials technology levels to temperatures as high as 1610 K (2438° F) were investigated; however, the final design of this system used relatively conservative technology with a turbine inlet temperature of 1242 K (1776° F), which is compatible with current superalloy materials capability for long-term operation. At this reduced temperature, the cycle efficiency was 21 percent. The satellite system mass was 102×10^6 kilograms for the 10-gigawatt system, or 10.2 kg/kW. Another Brayton cycle design used a 1652-K (2514° F) turbine inlet temperature with a cycle efficiency of 45 percent. This elevated temperature requires the use of materials such as ceramic (e.g., silicon carbide) that are currently under development. The total mass of this Brayton cycle satellite system was about 43×10^6 kilograms for a 5-gigawatt system, or 8.6 kg/kW, an indication of the weight advantage provided by more advanced technology.

The general conclusions made from the Brayton cycle studies are as follows.

[1] Satellite system mass with solar Brayton cycle energy conversion is competitive with photovoltaic options.

[2] Areas of concern in Brayton systems are (a) large, heavy radiator systems, including the requirement for leaktight fluid joints; (b) difficult requirements for efficiently constructing solar concentrators; and (c) low-packaging-density components (e.g., fluid ducts, radiator panels), which increase space transportation costs.

[3] In contrast to photovoltaics, hardware could be fabricated on an SPS scenario scale within current industrial capability.

(b) Rankine cycle: The system definition studies produced conceptual designs of Rankine cycle systems using potassium, cesium, and a cesium/steam (dual cycle) working fluid. The design features of a potassium Rankine cycle satellite system (ref. 5b) are shown in figure III-7.

The satellite system mass, without growth allowance, was approximately 81×10^6 kilograms for 10 gigawatts ground output. The design features of the potassium Rankine cycle system are summarized in table III-2.

The cesium/steam dual Rankine cycle concept is illustrated in figure III-8. The satellite mass for this concept was about 33×10^6 kilograms, without growth allowance, for 5 gigawatts ground output.

Conclusions made regarding Rankine cycle systems are as follows.

[1] Like the Brayton cycle system, Rankine systems represent acceptable alternative approaches for SPS solar energy collection and conversion.

[2] The primary disadvantages of the solar potassium Rankine cycle (relative to photovoltaics) are higher satellite mass and more difficult/complex space construction. Technology improvements that would make the potassium Rankine system more competitive are as follows.

[a] Development of easily constructed solar concentrators

[b] Development of high-temperature metal alloys with improved creep and creep rupture properties for thermal engine components - This improvement would yield higher system efficiency, which, in turn, would reduce satellite mass and cost as well as provide longer life potential.

[c] Fluid systems development such as lightweight radiators with leaktight joints, improved meteoroid protection for fluid tubes, and heat pipe technology - Novel radiator concepts such as dust and liquid drop radiators (ref. 29) may prove beneficial in this area.

The low projected mass of the cesium/steam Rankine dual-cycle satellite makes the concept competitive with the silicon and gallium arsenide photovoltaic options; however, satellite maintenance is a major concern for this system. The complexity associated with repair/replacement of a large number of massive components and potential problems of fluid system (leakage, cesium/steam interleaks) are major issues.

(c) Thermionics: Thermionic energy conversion was studied early during the system definition activities. A comprehensive system study conducted before the CDEP effort (ref. 25) produced several different thermionic SPS system concepts. Both solar and nuclear energy source systems were defined and analyzed. The following concepts were studied.

[1] Solar thermionic

[a] Direct radiation cooled

[b] Liquid-metal cooled

[c] Thermionic-Brayton cycle cascade, liquid-metal cooled

[2] Nuclear thermionic - molten-salt breeder reactor

Study of the thermionic energy conversion for SPS application was discontinued early in the program because results of the previously mentioned study and subsequent system definition studies showed that satellite mass is 1.5 to 2 times greater with thermionic conversion than with other thermal cycle systems and 2 to 5 times greater than with photovoltaic systems (fig. III-9). As a result, the thermionic system has a higher projected cost than other candidate systems because of high transportation costs. The major contributors to thermionic system mass are interelectrode busbar mass and radiator/pump systems for heat rejection (in liquid-cooled systems). The high electrode mass is a direct result of the low-voltage/high-current output characteristics of thermionic conversion. To make the thermionic system competitive, substantial improvements in electrode design and/or material would be required. The same is true for radiator/pump systems, which account for almost half of the satellite mass in liquid-cooled thermionic designs.

A comparison of satellite mass for the various energy conversion concepts is shown in figure III-9. Note that the masses shown are without growth allowance and are for a 5-gigawatt ground output system. The overall conclusions made from the energy conversion studies are as follows.

[1] Both photovoltaic (silicon or gallium arsenide) and thermal cycle (Brayton or Rankine) systems are technically feasible solar energy conversion methods. Photovoltaic system masses are competitive with solar Brayton and Rankine cycle system concepts. The estimated cost of photovoltaic systems is less than that of thermal cycle systems. Photovoltaic systems have higher reliability potential than thermal cycle systems because of the inherent redundancy features of photovoltaic array design and the passive system characteristics and because no active cooling system is required.

[2] The space construction cost is judged to be higher for thermal engine systems than for photovoltaic systems because a larger crew size and a larger construction facility are

required and because the packaging density of components is lower, resulting in increased space transportation costs.

[3] Maintenance considerations of the cesium/steam Rankine dual-cycle system pose difficult problems such as repair/replacement of a large number of massive components and potential problems of fluid system (leakage, cesium/steam interleaks).

[4] Thermionic conversion systems result in a satellite mass 1.5 to 2 times as great as with other thermal cycle systems and 2 to 5 times as great as with photovoltaic systems. As a result, the thermionic system has a higher projected cost than other candidate systems because of high transportation costs. The major contributors to thermionic system mass are interelectrode busbar mass and radiator/pump systems for heat rejection (in liquid-cooled systems). The high electrode mass is a direct result of the low-voltage/high-current output characteristics of thermionic conversion.

[5] Space nuclear reactor systems using rotating particle bed, molten-salt, and uranium hexafluoride breeder reactor systems with thermal cycle (Brayton, Rankine, and thermionic) offer the advantage of compactness relative to solar-powered systems; however, satellite mass, cost, and technical complexity are significantly greater (less attractive) than for solar-powered systems.

b. Power Management

The power management system collects, regulates, and controls power from the power generators (solar arrays or generators) and transmits this power by way of power buses through rotary joints with brushes and sliprings to the power transmission system. Limited energy storage is provided during eclipse periods. The system also provides for monitoring faults and fault isolations.

Power levels in this system are several orders of magnitude larger than in any previous space system. Although the engineering of such a system appears to be a monumental task, the insights gained from ground-based systems and from component-by-component analysis of the requirements placed on the SPS system indicate technical feasibility. This feasibility is conditional on successful component development and system operation at very high voltage levels. Initial studies in this area (refs. 1, 3 to 5, 18, and 30) investigated a number of trade-offs including dc versus ac power transmission on the satellite, alternative conductor materials, round versus flat conductors, transmission voltage/current effects, and power processing requirements. The significant conclusions of these studies are summarized in this section. Subsequent studies (refs. 7, 10, 14, and 26) emphasized definition and analysis of the reference system.

Figure III-10 is a schematic diagram of a typical solar array power collection and distribution system. The solar array power sectors are switchable to provide main power bus isolation for servicing. High-voltage breakers near the buses provide power controls. Power transfer across the rotary joint is accomplished by a slipring/brush assembly. Mechanical drive is produced by a large turntable. The antenna is supported in the yoke by a soft joint to isolate the antenna from turntable vibrations. The microwave power transmitting antenna includes a power distribution system, which distributes dc power from the sliprings to the dc to rf power amplifiers. Switchgear is provided for system protection and isolation for maintenance. The dc-dc converters are connected to voltage buses for power distribution to the power amplifiers. A typical power distribution system is shown in figure III-11.

The following are general conclusions resulting from SPS power management studies.

(1) High-voltage dc for klystrons.- Analysis has shown that high-voltage dc distribution provides a minimum-weight system for a photovoltaic SPS with a separate transmitting antenna. For a klystron antenna system, a nominal 40- to 45-kilovolt dc voltage level appears to be weight-optimum. The actual voltage will depend on the specific operating characteristics of the dc-rf power amplifiers, whereas the capability to employ these high voltage levels is contingent on further analysis and test relative to any plasma interaction effects.

(2) Low-voltage dc for solid state.- Solid-state dc-rf amplifiers operate at low voltages (25 to 200 volts dc). The use of such devices in a separate antenna causes a significant distribution and processing system weight increase because of the additional dc-dc conversion and low-voltage distribution requirements.

(3) High-frequency power processors.- Power processors must be operated at high frequencies (15 to 20 kilohertz) to achieve reasonable weight. Active cooling may be required to maintain the integrity of the dielectric materials so as to achieve acceptable reliability.

(4) Conductor materials.- Trade-offs in which electrical/thermal and mechanical performance, weight, cost, and availability were considered indicate that conductor-grade sheet aluminum of 1 millimeter thickness is preferred for the solar array power buses. Similar trades indicated that solid, round aluminum buses are preferred for the antenna power distribution (ref. 22).

(5) Technology advancement.- The following areas require technology advancement.

(a) High-speed switchgear: To protect the klystrons from fault currents, switching speeds measured in microseconds are required of the switchgear. State-of-the-art speeds are measured in milliseconds. The discrepancy between requirements and performance is considered the most significant switchgear problem (refs. 2 and 18).

(b) Spacecraft charging and plasma: Plasma-sheath electrons may charge up the satellite to high voltages, which may cause arcing shock hazards and other associated problems. Quantitative estimates of these effects have been determined for the reference system (ref. 31). Unresolved questions include high-voltage operation, satellite-induced environment, and acceptability of insulating material.

c. Orbit and Orientation

A geostationary orbit, with zero eccentricity and inclination, was selected for the reference system because it provides continuous power transmission and permits uniform (unaccelerated) motion of the transmitting antenna. Geosynchronous orbits with small inclinations and/or eccentricities offer possibilities of reduced shadowing of one satellite by another and of several satellites sharing a single synchronous orbit slot. These possibilities have not been evaluated in detail.

The satellite is oriented toward the Sun with the rotary joint axis always perpendicular to the orbit plane. This attitude minimizes gravity-gradient torque but results in an average loss of 4 percent of the incident solar energy from solar declination variations during the year (ref. 1).

Solar radiation pressure is the dominant orbit-perturbing force, requiring on the order of 50 tonnes of propellant per year if eccentricity is to be held at zero. By differential thrusting, this orbitkeeping impulse can be applied to attitude control, which would otherwise require nearly as much propellant itself. It also appears possible to depart from the POP orientation by several degrees without additional propellant expenditure, thereby reducing solar energy losses (ref. 7).

2. MICROWAVE POWER TRANSMISSION AND RECEPTION

The SPS reference system uses microwaves for power transmission from the SPS to the Earth's surface. A reference set of efficiencies has been defined that represents reasonable goals for each step in the power conversion-transmission-reception chain (fig. III-12). Because of thermal limitations on antenna materials, these efficiencies permit a peak microwave power density of 22 kW/m^2 at the transmitter. This limit, together with a limit of 23 mW/cm^2 at the ionosphere and the reference antenna taper, leads to a maximum power of 5 gigawatts per microwave link delivered to the power grid. This is the value selected for the reference system. There is evidence that 23 mW/cm^2 may be conservative (ref. 8); if so, the maximum power per link could be increased and/or the antenna size could be reduced.

The microwave power transmission system is the same for the silicon and gallium solar cell configurations. The mass of the reference MPTS is 17 000 tonnes, including margin.

For rf generation, the klystron was selected over the amplitron because of higher gain, lower noise, and higher output per tube. The magnetron appears promising but has not been examined as thoroughly as the klystron and the amplitron. Solid-state rf generators offer several advantages; they are discussed in Section III.C.2. A slotted waveguide array is the preferred type of radiating element based on high efficiency and simplicity. The waveguides are assembled into 10- by 10-meter subarrays; this size represents a compromise between the active mechanical alinement required for large subarrays and the greater phase control complexity of smaller subarrays. The reference system transmission frequency is 2.45 gigahertz.

A wide variety of transmitter power density tapers has been studied (ref. 9). A 10-step, 10-decibel Gaussian taper was selected for the reference system to maximize the amount of energy incident upon the rectenna and to minimize side-lobe peaks. The reference system used a retrodirective phase control system, although ground command and hybrid systems are promising alternatives.

The ground receiving station, or rectenna, is elliptical (except on the Equator, where it would be circular). The active area is 10 by 13.2 kilometers at 35° latitude plus a buffer zone to keep the microwave radiation exposure of the public below 0.1 mW/cm^2. The rectenna consists of dipole receiving elements and Schottky barrier diodes on a ground plane that is on panels with power distribution and conditioning equipment for the required interfaces with the power grid.

From a system standpoint, significant MPTS studies were conducted on system size (power output), multiple-beam concepts, operation and phase control concepts, cost sensitivity analyses, and transmission frequency effects. A discussion of the results of four of these studies is presented in the subsections that follow. Cost sensitivity analyses are discussed in Section IV.B.

a. System Sizing

The size of an SPS concept is generally expressed in terms of dc power output from the rectenna. This power output depends on several factors: operating frequency, system end-to-end efficiency, transmitting antenna size and power output capability, microwave power density limitations in the ionosphere (or at the Earth's surface), and rectenna size.

The appendix to this report provides a parametric analysis of the fundamental considerations of system sizing. As indicated in the analysis, the minimum unit cost system is the highest power system that can be designed within the constraints assumed. It should be noted that the costs used in this analysis are parametric values and not necessarily the same as those used in the reference system costing.

The system design point size selection has a significant influence on transportation and construction operations. For the reference design (photovoltaic silicon SPS and 1-kilometer transmitter) and for the reference launch vehicle with its available payload volume, it was just possible to package the entire SPS and its transmitter with subarrays preassembled on the ground. The packaging density of assembled subarrays is quite low, on the order of 25 kg/m^3 average. However, the packaging density of the photovoltaic blankets is very high, approximately 1200 kg/m^3. Detailed packaging studies show that mixing subarrays with high-density components allows all the flights to low Earth orbit to be mass limited. However, if (1) the transmitter diameter is increased relative to busbar power or (2) the thermal engine energy conversion system is selected or (3) an alternate vehicle with a smaller shroud is selected, it will be necessary to perform the final subarray assembly on orbit to avoid the high transportation costs associated with volume-limited launches. This in turn increases the on-orbit assembly crew and requires a subarray assembly facility. These items are discussed in subsection III.B.3.a.

Another study (ref. 11) investigated specific uses of smaller (less than 5 gigawatts) SPS concepts. The results of this study are discussed in the following paragraphs.

The satellite and the associated microwave system were optimized with larger antennas (at 2.45 gigahertz), reduced output powers, and smaller rectennas. Four constraints were considered: the 23-mW/cm^2 ionospheric limit, a higher (54 mW/cm^2) ionospheric limit, the 23-kW/m^2 antenna power density limit (thermal) in the antenna, and an improved thermal design allowing 33 percent additional waste heat. The differential costs in electricity for seven antenna/rectenna configurations operating at 2.45 gigahertz were studied. The conclusions of the study were as follows.

(1) Larger antenna/smaller rectenna configurations are economically feasible under certain conditions.

(2) Transmit antenna diameters should be limited to 1 to 1.5 kilometers for 2.45-gigahertz operation.

(3) Representative 2.45-gigahertz configurations with ionospheric power density limits of 23 and 54 mW/cm^2 have the following characteristics.

	23 mW/cm² limit	54 mW/cm² limit
Antenna diameter, km	1.36	1.53
Rectenna dc grid power, GW	2.76	5.05
Rectenna diameter, km	7.6	6.8
Relative rectenna area, percent	56	46
Electricity cost increase, percent . . .	50	17
Electricity cost, mills/kWh	70.6	55
Electricity cost, ¢/MJ	1.96	1.53

Note that the rectenna areas and electricity costs are in comparison to those for the reference SPS system.

The relative satellite and rectenna sizes and ground power output for different transmit antenna sizes at 2.45 gigahertz are shown in figure III-13.

b. Multiple-Beam Concepts

The concept of transmitting multiple beams from a single SPS antenna to multiple ground rectennas has been investigated to some extent. A large multiple-beam SPS system allows increased operational flexibility and greater economic payback. The number of SPS satellites and the size of an individual rectenna could be reduced. Multiple-beam antennas for communication and radar have been built and operated successfully. There are, however, problems unique to an SPS multiple-beam system that have not been in the analytical studies to date.

A number of techniques are available for splitting the beam as the linearity of electromagnetic fields is a well-known principle and allows the illumination of several spots from one aperture. The dimensions of the spots are limited by diffraction and depend on the transmitting aperture dimensions, the aperture illumination function, and the desired power transmission efficiency. The transmitting aperture can be considered as a screen across which a given field distribution may be defined. This distribution is determined by the field resulting from a sum of transmitting antennas behind the screen beaming through an opening in the screen toward their spots on the ground (fig. III-14). Alternatively, consider several apertures illuminating one screen and then apply reciprocity. In either case, synthesizing the beams consists of duplicating the required field pattern across the screen.

In general, the field pattern across the screen will be of uneven amplitude because of the addition and cancellation of phase fronts of different beams on the screen; that is, there is a diffraction pattern that must reproduce to obtain beam separation. For two beams of wavelength λ = 12.25 centimeters separated 2° (i.e., approximately 1600 kilometers (1000 statute miles) on the ground), there are diffractions, nulls, and peaks every 3.5 meters across the aperture screen. To implement this, the least controllable unit of aperture area (i.e., the subarray or power module) must be small compared to 3.5 meters; that is, on the order of 1 meter on a side.

The initial simulation results indicated that the main beam could be divided into two beams separated an equal distance from the antenna boresight. However, there was a residual peak at the site of the normal single beam that was attenuated only 20 decibels (a factor of 100). This residual pattern is not satisfactory for an SPS system and additional analyses are required. In addition, the possible generation of high grating l bes due to the formation of multiple beams off the boresight axis has not been studied.

The basic conclusions of the multiple-beam study are as follows.

(1) The use of multiple beams requires greater spatial resolution at the transmitting aperture. The resolution required varies as the angle between the most widely separated beams and will be on the order of 1 meter.

(2) In the case of ionospheric beam power limitation at the receivers and rf power density limits at the transmitter, satellite system design areas and powers scale as $N^{1/2}$, whereas the same parameters on the ground are a function of $N^{-1/2}$.

(3) To the first approximation, the cost of power is invariant with the number of beams.

(4) The advantages of multiple beams include increased operational flexibility, economic benefits, and fewer geosynchronous slot requirements. Disadvantages include a possible reduction in microwave transmission efficiency, increased phase control complexity, and increased sensitivity to ionospheric perturbations.

c. Phase Control Concepts

The forming, steering, and control of the SPS microwave beam are of major concern not only because of the power transfer efficiency considerations but also from a safety and environmental viewpoint. At the heart of the microwave power beam is the phase control system. This system, in essence, must adjust each radiating element's phase, automatically accounting for element location, antenna pointing error, surface roughness (mechanical alinement of subarrays), and phase distribution system delays.

The phase control system must accomplish three major functions: power beam forming, power beam pointing, and power beam safing (control). The generic or functional requirements in each of these major areas are fairly obvious. First, a highly directional, pencil-beam, microwave signal must be generated. In the SPS, this is accomplished by properly phasing each of the spacetenna's radiating power modules (or subarrays) to produce a broadside radiation pattern equivalent to the array beam shape.

Once a properly formed beam is achieved, the center of the beam must be precisely pointed at the Earth-based rectenna to efficiently transfer power. Since the mechanical pointing accuracy of the spacetenna and of the individual subarrays within the spacetenna is expected to be approximately 1 and 3 minutes of arc, respectively (ref. 30), the potential miss distance on the Earth's surface from geosynchronous altitude would be approximately 10 to 30 kilometers, which would completely miss the 10-kilometer-diameter rectenna site. To compensate for this pointing inaccuracy, the phase control system of the SPS must be capable of adjusting the phase of each radiating element power module to properly shift the power beam center without degrading the beam shape. The accuracy that must be achieved dictates development of new and highly sophisticated phase control techniques, which will be discussed later.

The final function that must be provided by the phase control system is that of power beam safing. This aspect is inherent in the phase control process since the power beam intensity is greatly diffused if loss of phasing occurs, because of excessive element-to-element phase errors. For example, if the phase error across the spacetenna exceeds 90° rms at the rf frequency, the array pattern has effectively diffused to that of a single transmitting element (power module) and the total energy is spread over an extremely large area. Although the power density at a given location far removed from the rectenna site may effectively increase when dephasing occurs, it will remain well below the U.S. and U.S.S.R. standards for radiation exposure at S-band (10 and 0.01 mW/cm^2, respectively), as shown in figure III-15. Thus, complete loss of phasing results in automatic safing as far as power density requirements are concerned. The other aspect of phasing loss which must be considered is that of partial dephasing or covert (jamming) dephasing. To protect against an intentional dephasing attempt or an attempt to redirect (rob) power, a method of coding each SPS pilot signal is included in the existing baseline system. To protect against the possibility of beam wander due to excessive phase errors during system startup or shutdown, some type of ground sensor network may be required in the vicinity of the rectenna sites. Thus, by using the concept of a retrodirective phase array system incorporating a coded (secure) pilot signal and ground sensors for additional safing considerations, the baseline SPS phase control system meets the general functional requirements discussed previously.

Achieving the phase accuracy necessary to meet the design goal power transfer efficiency ($\simeq$90 percent) will require advanced concepts and implementation techniques for the SPS phase control system. Two broad categories of phase control concepts have been investigated. First, techniques that employ phase corrections introduced at the transmitting array through ground system command links were considered. Several approaches to obtaining the phase estimate required for control of each transmit element's phase have been investigated. These include the following.

(1) Element phase estimation based on power beam pattern synthesis in the vicinity of the rectenna site (refs. 32 and 33)

(2) Multiple transmit frequencies for each radiating element to achieve phase estimation from traveling wave interferometer measurements (ref. 34)

(3) Direct phase measurement of individual element transmitted signals by sequential comparison of a coded (modulated) element's signal with the averaged phase of all other element signals at the rectenna center[1] (ref. 33)

At the present time, none of the ground-based phase control techniques have been thoroughly evaluated. However, the last two techniques, involving the interferometer-based technique for phase estimation and the sequential comparison of element signal phases using multiple tones to isolate the desired signal's phase from the power signal's phase, are being investigated.

As a result of the analytical, simulation, and test activities conducted to date, the following conclusions have been drawn with respect to the SPS phase control system.

(1) Beam misalinement (pointing error) is not critical when 10° rms phase error is achieved providing antenna/subarray mechanical alinement requirements are maintained.

(2) The upper bound on phase error is determined by acceptable economic losses in scattered power rather than by beam pointing errors or environmental factors.

(3) Based on the reference system configuration, for 10° rms phase error, the power lost from the main beam is less than 3 percent and the beam pointing error is less than ±250 meters with 99-percent probability.

(4) Phase control to the smallest transmitter area (power module for the reference system) reduces the grating-lobe peaks and relaxes subarray mechanical alinement and antenna positioning constraints.

(5) Phase control to the power module level is environmentally justified and economically sound based on cost trade-offs between phase control electronics and main beam power losses.

Regarding the retrodirective phase control concept, the following conclusions were reached.

(1) Implementation/performance appears feasible based on analytical simulations and experimental (laboratory) evaluations.

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[1]J. C. Vanelli: Scheme for Phase Control of Spacetenna Elements. Lockheed Electronics Company interdepartmental communication LEC-79-17-769-01.

(2) Secure operation can be achieved (coded pilot signal in reference system).

(3) Doppler effects are not a problem.

(4) Biases in the distribution system present a potentially serious calibration problem.

(5) Ionospheric effects on phase control are uncertain and could affect further system definition.

Features of the retrodirective concept include the following.

(1) Fast-response automatic phase tracking/adjustment

(2) Automatic/rapid fail-safe operation - Dephasing occurs in milliseconds and diffuses the power beam to 0.003-mW/cm^2 density levels.

(3) System complexity and performance criticality

Implementation/performance of the ground-based phase control concept appears feasible, based on analytical studies. Secure operations can be provided with a coded command channel. The ionospheric effects on phase control performance are uncertain and could affect further system definition. Biases in the distribution system can be adjusted out during normal operations (part of the phase control loop). Key features of ground-based concepts include the following.

(1) Closed-loop phasing (measure phase at ground and command phase adjustments through the communications link)

(2) Slower responses than retrodirective (0.25-second delay due to geosynchronous transit time)

(3) Dephasing process slower than retrodirective and may require additional beam safing measures

The hybrid (retrodirective and ground-based) phase control concept combines the best features of each of the concepts described previously; however, system implementation concepts and feasibility were not studied in sufficient detail for comparison with individual concepts (i.e.. retrodirective and ground-based).

The remaining phase control issues that must be addressed before selection of an SPS phase control system design concept are as follows.

(1) Phase error buildup in the distribution system

(2) Array topology for the distribution system (phase error buildup versus reliability)

(3) Cable versus fiber optics versus distributed signal

(4) Power signal interference on pilot signal receiver

(5) Phase conjugation accuracy

(6) Effects of ionospheric/atmospheric disturbances

(7) Alternate concepts to the retrodirective approach

(8) Accuracy of beam formation and pointing

(9) Failure effects on beam formation and pointing

(10) Radiofrequency interference (RFI) of the power module due to phase lock loop around the power amplifier

d. Transmission Frequency

Rectenna size can also be reduced by use of a higher transmission frequency. An industrial band at 5.8 gigahertz is potentially usable and has been investigated (ref. 11). Ionospheric heating is not a constraint, because of the frequency-dependent nature of the effect, but antenna heat rejection does limit the configuration. Transmission is satisfactory through a dry atmosphere but degrades severely in rainy conditions; the impact of such degradation on the power grid is not known. A reasonable 5.8-gigahertz system was derived that delivered 2.7 gigawatts to the grid with a 0.75-kilometer-diameter antenna and a 5.8-kilometer-diameter rectenna (ref. 11). The cost per kilowatt was estimated to be slightly more than that for the reference system. The relative antenna/rectenna sizes for 2.45- and 5.8-gigahertz operation are shown in figure III-16.

3. CONSTRUCTION AND OPERATIONS

A major consideration in selection of the reference configuration was ease of construction. The scale of the program mandates the highest possible degree of automation in the construction process; this in turn places a premium on highly regular configurations that can be constructed with a small number of frequently repeated operations. Ease of construction was, for example, one consideration in the selection of an end-mounted, rather than a central, antenna for the reference system. The repeatability of the photovoltaic configurations gave them a constructability advantage over the thermal systems, which require a relatively large number of different construction operations.

The reference system is constructed in geosynchronous orbit using material transported from low Earth orbit. The construction base is permanently manned by a crew of approximately 400 for construction, plus several hundred for maintenance of operating satellites. Construction in low orbit of sections of the satellite with subsequent self-powered transfer to geosynchronous orbit for assembly is an alternate approach, if radiation damage to the solar cells used for transfer can be annealed or otherwise reversed.

a. Satellite Construction Location Studies

The issue of where to construct the SPS received considerable study effort. Conclusions varied because of the sensitivity to assumptions and performance parameters.

Construction of the satellite in GEO offers many desirable features. Gravity-gradient loads are two orders of magnitude lower than in LEO, aerodynamic drag loads are not significant, thermal effects from passing through the Earth's shadow are much less frequent, collision hazard from other satellites is low, and the construction sequence should be simpler. Personnel logistics requirements, on the other hand, are greater than in LEO, but the percentage cost impact of personnel logistics is relatively low.

The most effective mode of construction in LEO is to build the satellite in modules sized to be compatible with the thruster requirements for the control of the SPS in GEO operation (fig. III-17). The modules are berthed together in GEO. Building the satellite as a complete unit in LEO for transport to GEO is not practical because of control requirements and loads to the structure due to gravity gradients.

Construction in LEO offers a potential cost saving by using a self-powered mode where the output from the partially deployed SPS solar cells is used to power a LEO-to-GEO propulsion system. The degree of degradation of the deployed solar cells by Van Allen belt radiation is an important parameter in the LEO-GEO trade. For self-powered transfer, the satellite solar array must be oversized to maintain the specified output or the cells must be subjected to an annealing process to restore efficiency. The use of an electric orbital transfer vehicle concept for GEO construction may reduce the cost differential between LEO and GEO sites; however, radiation effects also affect the efficiency of the EOTV.

Studies to date have indicated that either LEO or GEO construction appears feasible; however, a GEO construction location was used as the reference. The major elements and operations of the reference system GEO construction, which uses dedicated, reusable EOTV's, are shown in figure I-3.

b. Rectenna Construction

The rectenna is the ground-based unit of the SPS that receives microwave energy and converts it to grid-compatible electrical power (fig. III-18). Analysis indicates that a concept using individual antenna elements with dedicated rectifiers and filters for rf-to-dc conversion is preferred. These elements are mounted on flat panels arranged to be perpendicular to the incoming rf beam. A steel mesh is used behind these elements as an electrical ground plane. Elements are connected in parallel and series groups, as required, to produce voltage levels compatible with dc-to-ac conversion. The rectenna ground area varies with location and is elliptical because of its position relative to the equatorial orbit plane of the SPS antenna.

Rectenna site locations and alternative structural designs were investigated. The rectenna structure selected as a reference is constructed of steel with aluminum electrical conductors. Aluminum, wood, and concrete have also been examined for structural use. Several studies have been conducted on the availability of suitable sites.

(1) Site location studies.- A siting analysis was conducted to develop information on siting criteria and to make a preliminary assessment of siting problems. The three areas surveyed were the Pacific Northwest, the north-central region, and southern California. Information was informally exchanged with power companies in these areas. The analysis was conducted manually using aeronautical charts, contour plots, and roadmaps. From this study, it was concluded that the number of potential sites available exceeds the estimated requirements (ref. 12b).

A preliminary feasibility and cost study was performed on the concept of an offshore rectenna to serve the upper east coast. A candidate site was selected and several types of support structures were analyzed. Results indicate that a rectenna could be built offshore but that the practicality of this system is undemonstrated (ref. 35).

A number of studies have focused on site layout for typical locations. Maintenance facilities, access roads, converter stations, distribution towers, control buildings, and other similar factors were examined in the construction analysis (refs. 7f and 12b).

(2) Construction concepts.- Current reference system concepts for rectenna structure and construction techniques are based on standard methods of implementation (fig. III-19). Because of the large projected costs for these methods, automatic rectenna panel fabrication methods are desirable. Several studies have examined potential construction scenarios, various types of specialized heavy equipment, and manpower for rectenna fabrication. Specialized machines for rectenna fabrication are expected to provide significant cost-reduction benefits.

c. Operations and Maintenance

(1) Satellite.- The bulk of the SPS components are highly reliable, redundant, or relatively inert. Most satellite maintenance will involve periodic replacement or refurbishment of microwave antenna elements. Even though the reliability is fairly high, cumulative failures of these active elements over the SPS lifetime would result in an unacceptable degradation in performance. Alternative concepts for maintenance are a permanent maintenance base and crew at each satellite or mobile maintenance crews who return to one of the GEO construction bases with components to be refurbished. The latter concept is illustrated in figure III-20.

At the GEO base, maintenance workers board a mobile crew habitat. Together with maintenance equipment and replacement components, they travel to an operational SPS, which has been shut down before their arrival, and dock to the satellite's antenna. Using built-in equipment (e.g., cranes and cherrypickers), over a 3.5-day period, they remove defective components and replace them with new or rebuilt parts. Defective components are returned to the GEO base. The crew, mobile maintenance equipment, and replacement parts then move on to the next satellite, visiting as many as 20 satellites in a 90-day period, which is consistent with crew rotation time.

At the GEO base, other crewmen diagnose defective components, repair or replace them as appropriate, reassemble, and test. When possible, the refurbished components can be reused on other SPS's.

For 20 satellites, a mobile maintenance crew requires approximately 80 people with another 300 needed for the refurbishment work. The crew size varies with the number of satellites in service.

The primary components on the reference satellite that require maintenance are the klystron tubes and the dc-dc converters. These parts are removed from the satellite and transported to the GEO construction base, where they are refurbished. Maintenance of the solar cell blankets is not considered cost effective, because of the circuit redundancy inherent in the design. If degradation of the output of the silicon cells due to radiation becomes a factor in SPS output, the cells must be annealed or the array oversized. A concept for annealing the damage by heating the cells with a laser system was defined for the silicon system. On the gallium cell satellite, the cells are annealed by operating at a temperature high enough to cause self-annealing.

(2) Rectenna.- The rectenna provides the interface between the satellite and the electrical utility grid. Power generated in space must be transferred through the rectenna to the user in a controlled manner. Operations include startup, shutdown, and steady-state control under normal and emergency conditions. Extensive use of computer hardware will be required because of the extreme complexity involved in interfacing large amounts of power at very high speeds. All communications and telemetry will be interfaced through the rectenna control center. Rectenna operation under various conditions and maintenance has been studied. Direct-current power from rectenna rectifiers is collected by parallel and series interconnection into 40-megawatt power blocks. A group of 40-megawatt solid-state dc-to-ac inverters converts the power from these power blocks to alternating current. The synchronous operation of inverter output power with the utility grid is controlled in a manner to provide rectenna-to-grid power transfer. This management system will include devices for line phase, voltage control, and active controls for load shedding and line acquisition.

The SPS transmitting antenna and rectenna have been analyzed for all phases of operation. The operation and control of the two, in conjunction with grid particulars, determine startup, normal and emergency shutdown procedures, and steady-state operations.

During startup, the mechanical alinement of the antenna would be established and array temperatures allowed to stabilize. System status verification is followed by power-up of power processors, klystron heaters, magnets, and phase control system. The pilot beam is then acquired and rf drive confirmed. Power is ramped on in steps from the antenna center ring to outer edge in a timed manner as desired for grid load acquisition. This same technique may be used for system throttling. Klystron power is varied by controlling beam current with a modulating anode. In a shutdown, power is ramped down by klystron control, ring by ring from antenna outer edge to center; the pilot beam is disrupted; the circuit breakers are opened; and power is transferred from on orbit to storage if required. During an emergency shutdown caused by grid operations such as a load trip, the rectenna elements would shift power to resistive load banks, the pilot beam would be disrupted, and onboard circuit breakers would be tripped.

Operation will involve a very high reliability of transmission and power absorption into the grid to avoid SPS power throttling. Because of the high probability of never having a complete power loss from an SPS, the needed grid reserve might decrease with increasing SPS grid penetration (ref. 12f).

Maintenance for SPS and rectenna systems can be limited to performance during scheduled downtimes only if grid penetration is sufficiently low to maintain operation with adequate generation reserve.

Because of the high probability of lightning striking a rectenna and the potential for damage to various low-voltage elements, special provisions must be made for adequate lightning protection (ref. 31).

4. SPACE TRANSPORTATION

In the reference system, transportation to low orbit is accomplished by a two-stage winged heavy-lift launch vehicle with a payload of 420 tonnes. A ballistic HLLV was also considered, but ocean recovery introduces operational complexities and the winged HLLV can also be used for personnel transport, eliminating the need for development of a personnel launch vehicle. From the low-orbit staging base (fig. I-3), EOTV's transport 4000 tonnes of cargo per flight (one launch every 11 days) to synchronous orbit. Radiation damage to the EOTV solar cells during the passage through the Earth's trapped radiation belts will be severe, but the EOTV offers a substantial cost saving relative to chemical propulsion. Personnel are transferred by chemical rocket to minimize travel and radiation exposure times.

The history of SPS launch vehicle evolution is shown in figure III-21. Early studies of SPS launch vehicles examined ballistic systems shaped like large Apollo spacecraft; these were to return to Earth engines-first by aerobraking and land at sea for recovery by ship. Single-stage and two-stage options were examined. The performance of the two-stage systems was sufficiently superior to more than offset their greater operational complexity.

Later, comparison of winged and ballistic launch vehicles led to the conclusion that the winged systems were preferred. Although more expensive per unit, the shorter turnaround time of the winged systems permits a smaller vehicle fleet, effecting overall savings. This trade resulted in selection of the two-stage winged vehicle now represented as the SPS reference launch vehicle. The size of the vehicle was somewhat arbitrary. The only specific consideration was selection of a payload bay large enough to accommodate a fully assembled electrical slipring, 16 meters in diameter. The payload capability of the reference vehicle was estimated as 420 gross tonnes, with an effective net payload of about 360 to 380 tonnes after accounting for the mass of payload pallets, propellant containers, and similar factors.

Alternative vehicle designs were created in other studies. The most important are (a) a parallel-burn, crossfeed configuration; (b) a single-stage-to-orbit airbreathing/rocket runway takeoff vehicle concept; and (c) a smaller HLLV concept. The parallel-burn configuration yields about 10 percent improvement in payload capability at a given lift-off mass but involves increased operational complexity. An adequate trade-off to select between series and parallel burn has not been conducted. The airbreather concept was representative of vehicle designs that might be attainable with highly advanced propulsion and structures technology.

The smaller HLLV was analyzed to compare the nonrecurring cost benefits of a less challenging development with the recurring cost increases expected because of losses in efficiency associated with smaller vehicle size. The vehicle payload bay size was selected to be adequate to accommodate the SPS transmitter subarrays fully assembled. This configuration required a square cross section of 11 meters; the length was set at 14 meters. Parametric investigations led to a gross lift capability requirement of 120 tonnes. The resulting vehicle design is compared with the Shuttle, the Saturn V, and the reference SPS HLLV in figure III-22. Analysis of this concept indicated that nonrecurring saving of at least $5 billion was obtained with a recurring cost penalty of 3 percent per SPS relative to the reference system. Further, the environmental benefits of the small vehicle - reduced sonic overpressure, noise, potential blast effect in the event of an accident, and less modification of the Cape Canaveral area to accommodate launch pads - were deemed more important than the slight increase in upper atmosphere propellant deposition. As a result of the conclusions, it was recommended that the small HLLV be adopted as the SPS reference launch system.

5. CREW CONSIDERATIONS

a. Radiation Protection

The Earth magnetosphere and the radiation sources to which SPS systems and the GEO assembly and maintenance crew will be subjected are shown in figure III-23. The major sources of radiation at GEO are the geomagnetically trapped electrons and protons, galactic cosmic rays, and solar flare event particles. At geostationary orbital altitudes, the trapped radiation particles undergo large temporal fluctuations (diurnal and during magnetic storm activity). The types of ionizing radiation important to SPS operations include the following.

(1) Electrons and secondary radiation: bremsstrahlung (with variation of a factor of 2 due to parking longitude location)

(2) Protons (flux from solar flare protons dominates), secondary radiation protons, and neutrons

(3) High-energy heavy ions (HZE), secondary radiation: protons, neutrons and lighter nuclei

The allowable crew radiation exposure criteria and radiation protection techniques for the GEO base are discussed in the following paragraphs.

(1) Radiation exposure limits.- Astronaut radiation exposure limits defined by the National Academy of Sciences/Radiobiological Advisory Panel/Committee on Space Medicine in 1970 are listed in table III-3. These astronaut radiation exposure limits are based on a 5-year career and are presently included in the STS Payload Safety Guidelines Handbook. These limits are, of course, intended to cover all forms of ionizing radiation (natural and induced). Comparable radiation exposure limits are also shown for industrial workers, as defined by the Department of Labor Occupational Safety and Health Administration (OSHA) regulations. The low OSHA limits are also contrasted with the maximum radiation limit allowed for each Apollo mission.

It is interesting to note that the average skin dose experienced by the Apollo astronauts was very low (about 1 rem), since no solar event occurred. Nevertheless, the maximum limit for Apollo was established for a program of national importance that included less than 100 volunteer astronauts. The OSHA standards, of course, apply to millions of industrial workers. The SPS construction base is presently estimated to have approximately 800 workers on board, which equates to a 10 000-man work force over a 30-year period. Hence, allowable SPS radiation limits may have to be established with respect to societal considerations.

(2) Shielding for GEO trapped electrons.- The average rem dose that a crewmember will experience each day in geosynchronous orbit is plotted as a function of equivalent aluminum cabin wall thickness in figure III-24. To reduce the skin dose to 1.11 rem/day for the maximum quarterly exposure limit (i.e., 105 rem less 5 rem for OTV LEO/GEO transit), at least 10 millimeters of aluminum should be provided. Aluminum is not a very effective shield for this level of radiation because of bremsstrahlung (secondary radiation) effects. However, by adding a thin inner layer of tantalum (Ta), the cabin radiation level can be lowered to provide a margin for other unscheduled radiation conditions (e.g., X-ray inspection). The use of compound wall design techniques is an effective way of coping with bremsstrahlung that provides increased radiation protection for minimum shield thickness and weight. Practical shielding designs that can reduce the daily dose rate to OSHA levels require further study and remain as a technology issue.

(3) Solar flare radiation protection.- The GEO base solar flare radiation protection system must be capable of providing timely warning of a high-energy solar event so that the crew can safely reach a radiation shelter to ride out the storm. The characteristics of a typical solar event are shown in figure III-25 together with related data on the severity and duration of prior solar events. Minimum aluminum shielding thickness requirements are provided.

Once a solar flare is observed, a 20- to 30-minute delay occurs in particle propagation before an increase in the background energy level is detected. From the onset of increased radiation, the maximum flux level may be attained within 15 minutes to a few hours according to Wilson et al. (ref. 36); some investigators have reported from 2 to 100 hours. The corresponding time delay for the first particle to arrive is approximately one-third to one-half the time to reach peak intensity. The peak intensity, in turn, may last only intermittently or for a few hours, and the subsequent decay period may be over in a matter of hours or days. Data from the 20th solar cycle show that the highest energy event recorded lasted for 5 days and that a few lower energy events lasted 10 days. Hence, the radiation storm shelter must be capable of supporting the crew life support functions for several days.

In the upper right part of figure III-25, the frequency of solar events is plotted as a function of the severity of the event (protons per square centimeter). Smoothed historical data are shown for the two most recent solar cycles. Cycle 21 is now underway and resembles cycle 19 rather than cycle 20. The lower right part of figure III-25 shows the cabin wall thickness necessary to protect against this range of event sizes. A typical cabin wall thickness needed for shielding trapped electrons in GEO is also shown at 2.6 to 4 g/cm^2 (i.e., 1.0 to 1.5 centimeters of aluminum). A 4-g/cm^2 shield gives protection for any event up to 1×10^9 protons/cm^2 flux; however, a minimum thickness of 10 g/cm^2 is needed for a major solar event (Aug. 1972) provided the crew is also equipped with personal shielding for the eyes and testes during peak exposure. Development of a real-time solar flare alert system with a flux forecast is needed. If the alert system can be triggered at predetermined energy levels below the nominal wall radiation protection level, then a built-in margin for error in forecasting accuracy could be achieved.

(4) SPS GEO base radiation design considerations.- The allowable crew dose for the SPS GEO construction base remains to be established. Total accumulated dose limits are required for the entire mission profile; that is, time in LEO, in LEO/GEO transit, and at the GEO base. How much margin should be provided for unscheduled exposure and whether the astronaut allowed radiation levels are applicable to SPS are areas for further study.

Protection against trapped electron flux in geosynchronous orbit must be factored into all aspects of GEO base operations and design, which include intravehicular-activity (IVA) assignments in remote work stations, free fliers, crew buses, and crew habitation modules. A multilayered cabin wall of 2.6 g/cm^2 aluminum equivalent is recommended for the crew module. The other IVA crew stations could be designed with lighter shielding provided the total allowable dose is not exceeded. In addition, if extravehicular-activity (EVA) operations are needed, they should be conducted near local midnight to minimize normal belt radiation exposure. However, EVA should be avoided during large-scale fluctuations due to geomagnetic disturbances. The present SPS suit must be upgraded to provide added protection for GEO EVA (i.e., between 1.5 and 4 millimeters equivalent aluminum).

Protection against solar flares requires an adequate flare alert warning system that will allow all GEO base workers on remote IVA or EVA assignments to retreat to the nearest storm shelter. Means for protecting stranded workers at these remote locations need to be considered together with the systems required to implement their rescue. The storm shelter is provided with 20 g/cm^2 of multilayered aluminum equivalent thickness. Additional shielding benefits can be attained by placing internal equipment arrangements against the outer wall.

Protection against high-energy heavy ions requires further study. Although the dose from these HZE particles is small, it is important because of possible biological effects.

b. Crew Habitat Description

As mentioned previously, a large number of space workers will be required during the satellite construction and maintenance periods. In the reference system, where satellite construction is accomplished in geosynchronous orbit, workers will be stationed in GEO and LEO. The following is a description of the reference system crew quarters and support systems.

(1) GEO base.- The GEO construction base will construct one 5-gigawatt SPS in approximately 6 months employing a crew of 444 people. The GEO base will also be used as a place to refurbish disabled SPS hardware and will be the home base of maintenance crews and their mobile maintenance system that travels to operational SPS's.

One transient crew quarters module and four habitat modules are provided to house all members of the two-shift GEO construction crew (444). When 20 satellites must be maintained, the GEO support crew (383) will require 3 more habitats and another transient crew quarters module. These supporting crew modules will eventually increase to 9 habitats and 3 transient crew quarters when 1149 people are needed to maintain 60 satellites.

Each module (fig. III-26) is sized to accommodate about 100 people depending on the number of single- and double-occupancy staterooms provided. The 23- by 17-meter-diameter domed-end cylinder is arranged with seven decks, each having a 2.2-meter floor-to-ceiling height. Three decks are allocated to living quarters for male and female personnel. Galley and dining areas are provided on another deck that also serves as a radiation storm shelter for 100 to 110 people. The other decks can be arranged to include a backup control center; recreational, physical fitness, and services areas; and subsystem equipment rooms as needed. Each deck is accessible to the adjacent decks through three 1.5-meter-diameter openings. Alternate decks are provided with external hatches that can lead to interconnected crew modules, berthed crew-transfer vehicles, or attached airlocks.

Each crew module operates almost independently except for primary electrical power and orbital attitude, which are provided by the base. Emergency power, environmental control and life support (ECLS), and information subsystems are self-contained within each module. The 100-man module described in reference 12c had been scaled from prior study on 12-man unitary space stations. Crew-area allocation studies indicate that accommodations for 100 people in a 7-deck module compare favorably with current U.S. Navy ship design practice and with requirements from prior studies. A regenerative ECLS subsystem, which includes closed water and oxygen loops, is defined to provide life support and thermal control for 100 men. The subsystem is capable of maintaining sea-level pressure conditions with minimal expendables. A multilayer cabin wall (2.6 g/cm^2 aluminum) protects the crew against micrometeorites and trapped electron radiation. Protection against solar flares is provided by a storm shelter using 20-g/cm^2 shielding.

(2) LEO base.- The LEO base is used to construct the EOTV's and is also used as a staging depot for transferring cargo and crews to the vehicles that will deliver them to GEO. During the EOTV construction operation, there would be approximately 230 people at the LEO base; during the ongoing cargo-handling phase, there would be approximately 135 people at the LEO base.

A total of 5 crew modules would be required at the LEO base: 3 crew-quarters modules each having a 100-man capacity to house the 230 LEO base crew and serve as transient crew quarters, 1 operation and maintenance module, and 1 training module. The modules will be identical to the corresponding GEO base crew modules with the exception that the storm shelter shielding would be deleted from the crew habitats.

C. ALTERNATE CONCEPTS

1. POWER LEVEL AND TRANSMISSION FREQUENCY

As discussed in Section III.B.2, the power level (size) of an SPS is determined primarily by microwave system parameters. Cost and mass optimization studies showed that 5 gigawatts ground output is the most cost-effective size for the microwave system using tube-type generators and the power beam parameters outlined in Section III.A. For a detailed discussion of alternate antenna/rectenna configurations, see Section III.B.2.

2. SOLID-STATE AMPLIFIERS

The klystron microwave generators in the reference system dominate the anticipated maintenance requirements of the SPS (ref. 12b). Since solid-state components typically have much higher mean times between failures than conventional electronic tubes, their use in the MPTS could greatly reduce maintenance time and personnel. They also offer the potential for mass production as part of an integrated circuit.

Three main problems must be solved to make solid-state transmitters practical for SPS use. The first is the low voltage of the solid-state devices themselves. Because of efficiency limits, early investigations eliminated from consideration the few hybrid kinds of devices that can operate at relatively high voltage and converged on gallium arsenide field-effect transistors (GaAs FET's) as the most promising devices because they hold promise of reaching higher efficiencies at SPS frequencies than other devices for which appreciable practical experience exists. Gallium arsenide FET's operate at approximately 15 volts, with efficiencies (dc to rf) of 72 percent demonstrated in the laboratory. (The parametric studies used estimates for conversion efficiency of 80 percent as reasonable extrapolations of present experience.) The distribution of dc electric power on the SPS should be done at several kilovolts to avoid excessive conductor mass and high resistive losses in the power conductors.

The second problem is the temperature limitation of solid-state devices. Operating temperatures allowable for GaAs FET's consistent with long life are limited to 398 K (125° C) or less, limiting the waste heat rejection power per area of the transmitting antenna to approximately 1.5 kW/m^2. By comparison, the reference (klystron) system rejects 5.5 kW/m^2 of heat at more than 573 K (300° C). As a result, with a conventional 10-step, 9.54-decibel Gaussian taper, solid-state systems are limited to power levels in the 2500-megawatt range. Careful attention must be given to the thermal paths in the detail design of power transmitting elements in order to minimize the temperature drop from devices to heat-rejection surfaces so as to maximize the effective heat-rejection surface temperature.

The third problem is the low power of the solid-state amplifiers. Although 15-watt GaAs FET's have been made (ref. 37), RCA has estimated that for efficient devices, the output per device will be on the order of 5 watts. The power is limited by the very small dimension of the active area in the GaAs FET chip. Even in 5-watt devices, large numbers of channels are operated in parallel. The power level per antenna element (i.e., dipole) required on a 2.5-gigawatt SPS is greater - 10 to 20 watts. Thus, combining the outputs of individual amplifiers in antenna elements is likely to be required. Conventional combining schemes incur additional losses on the order of 10 percent.

Design and limited technology work conducted in the system definition efforts developed technical approaches to resolving the previously described problems. One approach is to replace the reference antenna with a solid-state version. Because solid-state devices require a lower operating temperature than the klystron, the optimum solid-state system has a larger transmitting antenna, a smaller rectenna, and lower total power output. Using the reference 10-decibel Gaussian taper, typical values are 1.4 kilometers, 7 kilometers, and 2.5 gigawatts, respectively (ref. 5b). Because of the low voltages required by solid-state devices, the power distribution system must pay a substantial mass penalty (thousands of tons) in conductors and in dc-dc conversion equipment. The overall configuration and key components of this concept are illustrated in figure III-27.

The power distribution penalty can be minimized by the "sandwich" concept (ref. 7), in which solar cells are mounted on one side of a substrate and the solid-state power amplifiers on the other, with direct electrical power connections between small groups of cells and amplifiers. To illuminate the solar array while the antenna points continuously at the ground, a system of reflectors is required. By using multiple reflecting paths, concentration can be achieved. Figure I-4 shows one proposed configuration that delivers 1.2 gigawatts to each of two rectenna sites that are 5 kilometers in minor diameter.

The solid-state-sandwich concept is predicated on a combination solar cell/microwave transmitter-antenna panel, thus eliminating the large, high-power, main conducting cables and the corresponding high-power sliprings required in the baseline reference configuration. The associated ground receiving sites are schematically identical to those defined for the reference concept, except that individual sites are sized to accommodate their specific satellite capability.

The satellite configuration consists of two smaller satellite configurations joined together to provide a "balanced" configuration relative to certain attitude control considerations. The major advantage is that solar pressure moments will be reduced (when compared to those developed by two independent satellites maintained in the stationkeeping mode), resulting in lowered propellant requirements.

The major features of the solid-state-sandwich configuration are a large mirror (reflector) system, consisting of an eight-segment primary mirror and a single secondary mirror delivering an effective concentration ratio (CR_E) of approximately 5.2, and a "coupled" solar cell/microwave antenna panel. The microwave system is made up of approximately 4×10^8 solid-state amplifiers/antennas located on 7.81-centimeter centers.

One major disadvantage of the sandwich concept is the difficulty in tapering the transmitter power density for side-lobe suppression without reintroducing power distribution penalties. Consequently, uniform illumination is used. A second major disadvantage is that the output power from the rectenna is about one-fifth that from the reference system. The rectenna land areas are the same because of the uniform illumination taper. A 10- by 13-kilometer perimeter is necessary to contain illumination levels above 0.1 mW/cm^2 with the system shown in figure I-4.

3. LASER POWER TRANSMISSION

Laser power transmission was not studied to the same level of detail as the microwave transmission system. The potential use of lasers provides an alternative to microwave power transmission that offers two potential benefits. Economically, the most important is that laser power transmission may provide a means of transmitting much smaller blocks of power than is practical with microwaves. This could broaden the potential market for

SPS power to include users that cannot handle thousands of megawatts of power per generating unit. The second potential advantage is that the laser option is not subject to concerns regarding the possibility of long-term low-level microwave energy effects on the environment.

These potential advantages are counterpoised by major issues. Perhaps foremost is the difficulty of achieving high-efficiency power transfer. State-of-the-art continuous-operation lasers such as CO_2 EDL's operate at efficiencies on the order of 20 percent, whereas the comparable microwave system is expected to operate at about 85 percent. Similar problems exist at the receiving end; microwave-to-dc conversion is expected to be about 89 percent efficient, whereas laser light conversion efficiencies over 50 percent may be difficult to achieve. Other important issues include the laser system complexity and personnel and public safety, as well as the availability of laser power considering atmosphere propagation characteristics.

In the efficiency area, it is important to find a means of substantially improving at least one end of the link. Several means have been suggested. Some of the more significant are as follows.

a. Use of a free-electron laser - The ideal efficiency of FEL's is quite high, similar to microwave converters.

b. Direct optical pumping of the laser by sunlight (or indirect pumping through a cavity absorber within which the laser is pumped by spectrum-shifted light) - This approach eliminates the solar array and the laser efficiency may then be comparable with that of the combined solar array/microwave system.

c. On the ground end, conversion by very high efficiency heat engines, by optical diodes, or by photovoltaics tailored to the laser frequency

Some combination of these options would appear to offer considerable leverage in improving the efficiency picture.

Safety and availability issues are both subject to amelioration by suitable frequency selection and avoidance of very high intensities on the ground. Thus, the analysis must consider frequency selection for safety as well as for device compatibility and efficiency factors.

The types of lasers considered in the study and an initial "screening" assessment of each type are given in table III-4. As indicated, gas electric discharge lasers, optically pumped lasers, and free-electron lasers were selected for design analysis.

Electric discharge lasers require electric power to drive a high-voltage discharge that pumps the laser medium to an excited discharge state and to circulate the lasant through a cooling loop to remove waste heat. For this type of system, a solar array may be employed to produce the power. This type of system is extremely inefficient, resulting in a large solar array and large radiators. The result is a system mass and cost that is not competitive with microwave power transmission systems.

Direct solar-pumped lasers also are inefficient because of the narrow lasant spectral band and the broad spectral characteristics of solar energy. For this reason, an indirect solar-pumped approach is used to achieve more compatible spectral characteristics. Solar energy is focused by reflectors into a cavity collector (fig. III-28). A temperature is achieved in this cavity that releases thermal radiation in the spectral region that excites the lasant. Efficiencies of this system are considerably improved.

The final laser system, the free-electron laser, is shown in figure III-29. In this concept, an electron beam is formed (using a klystron as the electron source, which is accelerated in an rf accelerating cavity) that produces laser frequency energy on passing through a magnetic field that causes lateral electron movement. The beam is directed to mirror assemblies on each end of the satellite that form a laser beam, which is directed to a receiving station on the Earth. The solar array provides the energy that powers the system. The system on the ground for conversion of laser to electrical energy uses optical diodes that are analogous to the microwave rectenna. Conversion efficiencies are similar to those of the rectenna system. This system appears to provide the highest efficiency and lowest mass of all laser systems studied.

The specific masses of the laser concepts and the reference silicon solar array concept that uses klystrons for dc/rf microwave conversion are compared in figure I-5. Current estimates made by the Boeing Company indicate that the lowest mass laser concept (free-electron laser) is about twice the specific mass of the reference concept. Additional laser systems studies are needed to determine approaches that may lead to reduced mass and cost to make them more competitive with the microwave SPS concepts. In addition, because of the problems related to penetrating heavy cloud layers, total power system integration studies are needed to determine the degree to which a laser system might penetrate the utility network.

TABLE III-1.- SOLAR CELL TRADE-OFF COMPARISONS

Solar cell			CR	Annealing	Cell area, km^2	Mass,[a] kg	Cell parametric cost, $\$/m^2$	Relative cost[b]
Type	Efficiency, percent	Specific mass, kg/m^2						
GaAlAs	[c]20	0.252	1	Yes	44.31	15.81×10^6	71	1.26
GaAlAs	[c]20	.252	2	Yes	26.52	13.55	71	.91
Silicon	[d]17.3	.421	1	Yes	52.33	27.06	35	1.0

[a]Includes solar cells, reflectors, primary and secondary structure, and power distribution only.
[b]Includes energy conversion, power distribution, support structure, and transportation ($40/kg to GEO).
[c]At 301 K (28° C) air mass zero (AMO).
[d]At 298 K (25° C) AMO.

TABLE III-2.- POTASSIUM RANKINE CYCLE DESIGN FEATURES, 10-GIGAWATT SYSTEM

Turbine temperature, K (°F)	
Inlet	1242 (1776)
Exhaust	932 (1218)
Turbogenerator	
Nominal size, MW	31.4
Quantity per SPS	[a]576
No. of modules per SPS	16
Radiator projected area per SPS, km^2	1.15
Cycle efficiency	0.189
Reflector facets	
Material	Aluminized Kapton
Thickness, μm	2.5
Quantity	116 000
Total area, km^2	119
Satellite orientation[b]	Perpendicular to ecliptic
Power distribution	
Potential, kV	40
Description	Passively cooled, dedicated aluminum sheet conductors; antenna joints incorporate diurnal axis with slip-rings and annual axis with wind-unwind cables
Maintenance	Malfunction detection system for shutdown of individual turbogenerators as required; periodic maintenance

[a]Six are "reserve."
[b]Electric thrust.

TABLE III-3.- RADIATION EXPOSURE LIMITS AND CONSTRAINTS

[rem]

Period	Astronaut (a)			Apollo max. limit - BFO[b] and skin	Industrial worker - BFO and eyes (c)
	Skin (0.1 mm)	Eyes (3 mm)	Bone marrow (5 cm)		
1-yr av daily rate	0.6	0.3	0.2	--	--
30-day maximum	75	37	25	[d]65, 520	--
Quarterly maximum	105	52	35	--	3
Yearly maximum	225	112	75	--	5
Career	[e]1200	600	400	--	[f]235

[a]Source: Space Transportation System Payload Safety Guidelines Handbook, JSC-11123, July 1976.

[b]BFO = blood-forming organs.

[c]Source: Federal labor regulations, part 1910 OSHA, July 1, 1978.

[d]Per mission. Average crew skin dose for Apollo missions 7 to 17 was only ≈1 rem since no major solar particle events occurred.

[e]5 years.

[f]At age 65.

TABLE III-4.- LASER OPTIONS, FIRST SCREENING

Laser option	Status	Reason
Glass or ruby	Rejected	Low efficiency; large mass
Chemical	Rejected	Not suited for steady-state operation
Excimer	Rejected	Low efficiency
Solid state	Rejected	Low power per device; low voltage; complexity
Gas dynamic	Rejected	Low efficiency; large mass
Gas electric discharge	Selected	Potential for high power and fair efficiency
Gas optically pumped	Selected	Elimination of solar array
Free electron	Selected	Potential for high power and good effic.ency

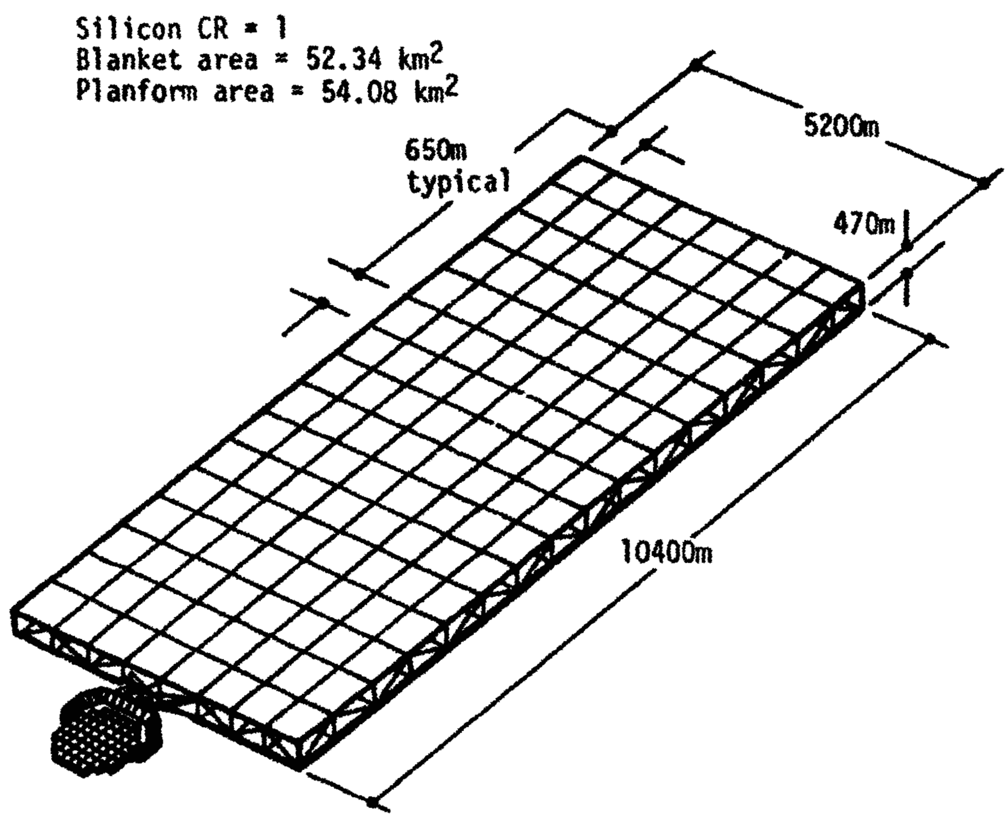

Figure III-1.- SPS reference system - silicon cell.

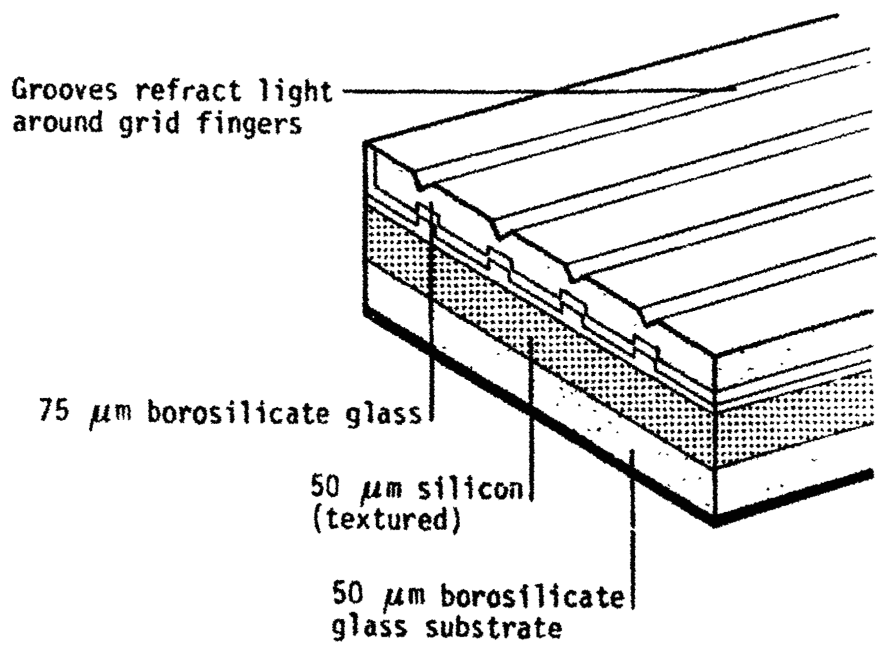

Figure III-2.- Silicon solar cell blanket.

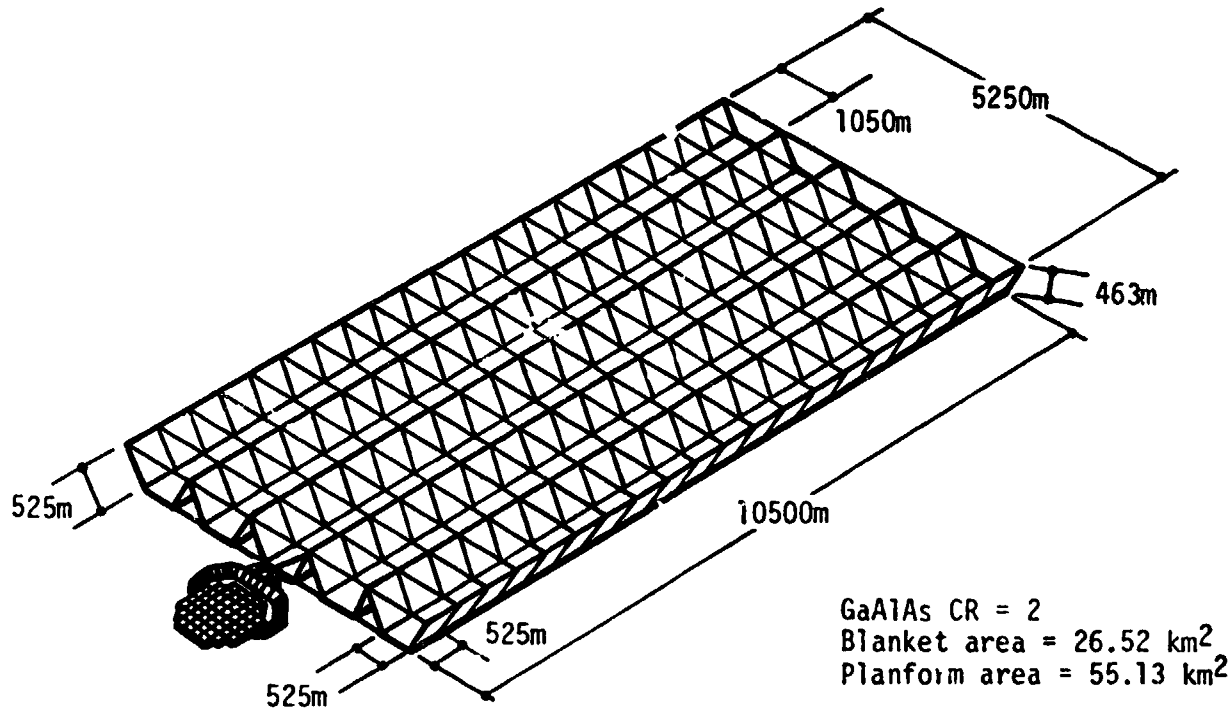

Figure III-3.- SPS reference system - gallium arsenide cell.

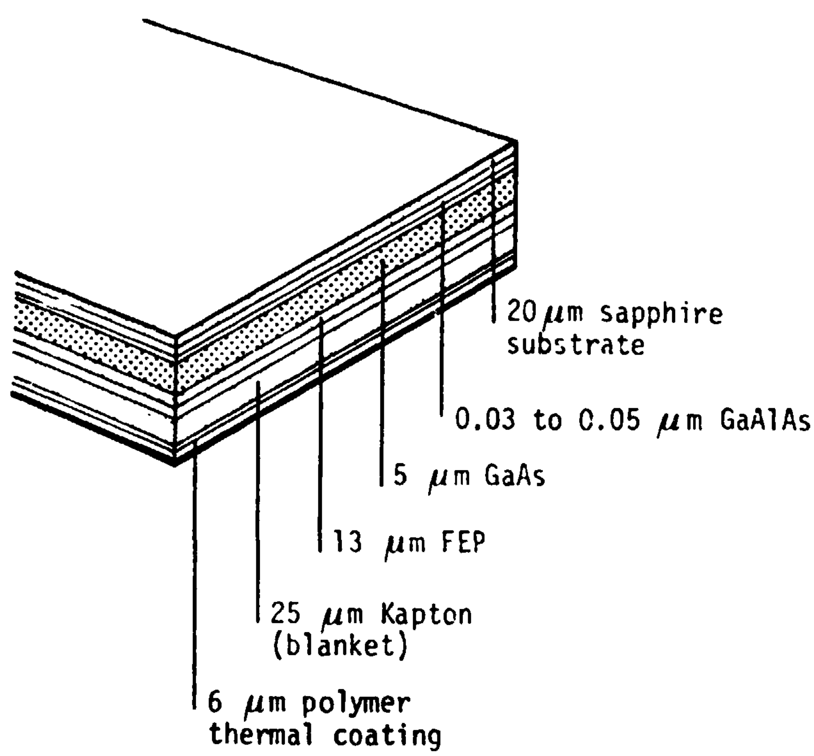

Figure III-4.- Gallium arsenide solar cell blanket.

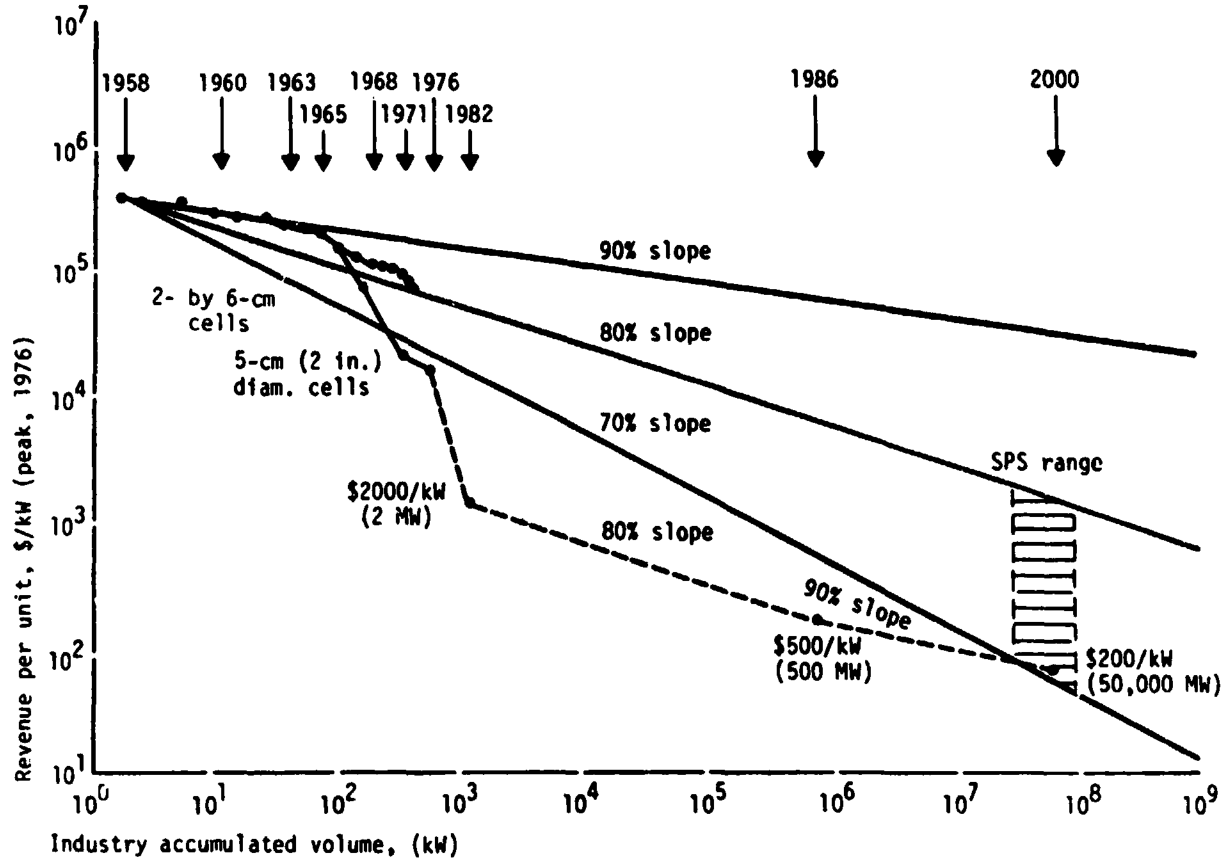

Figure III-5.- Cost-reduction projections based on industry experience (ref. 28).

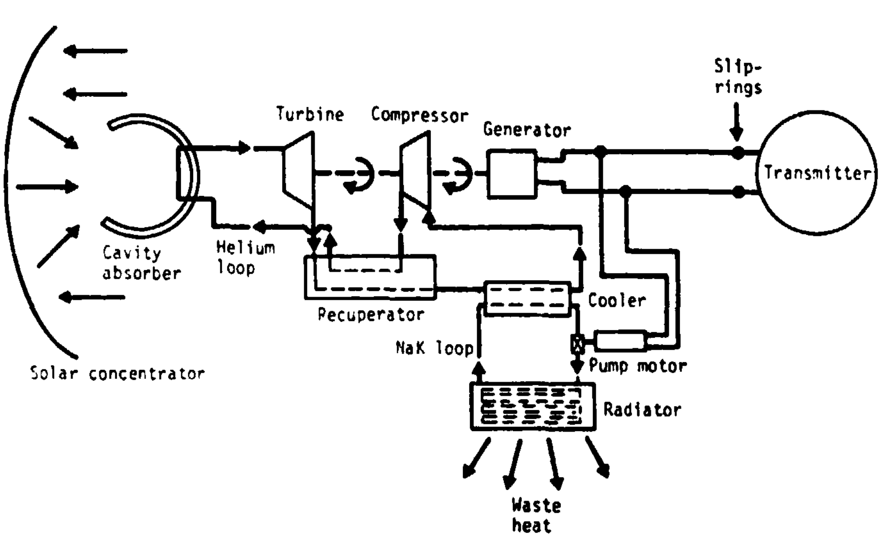

Figure III-6.- Solar Brayton cycle - helium.

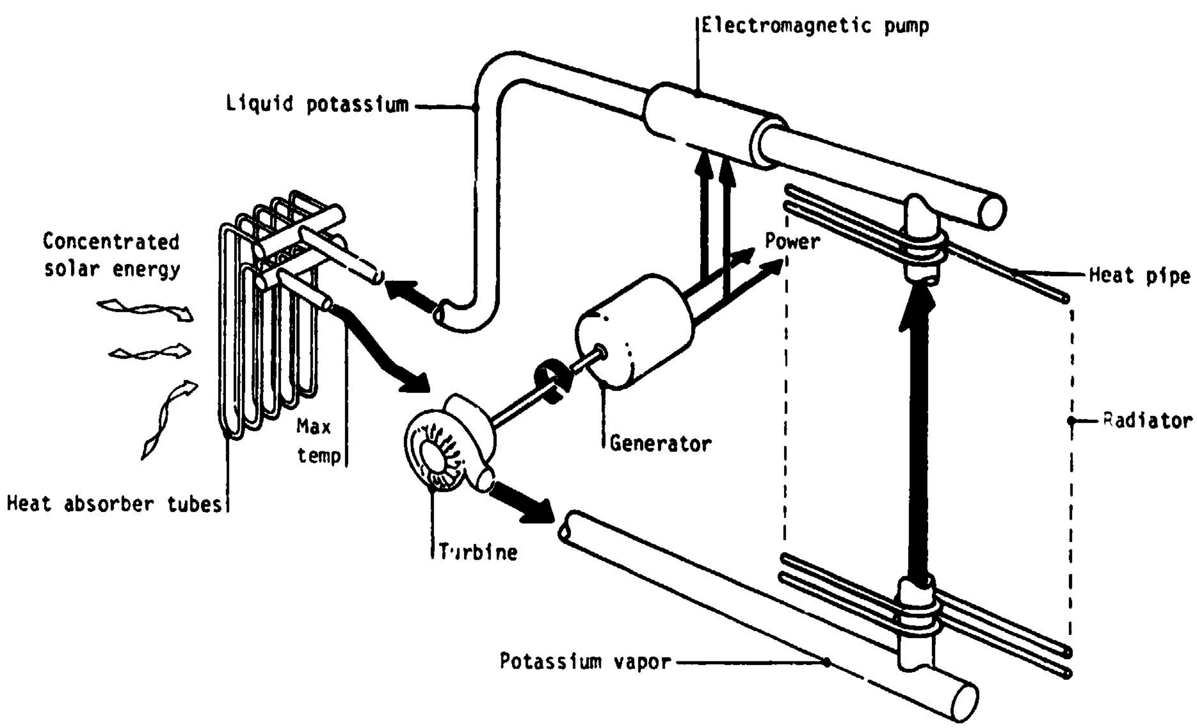

Figure III-7.- Rankine cycle schematic - potassium.

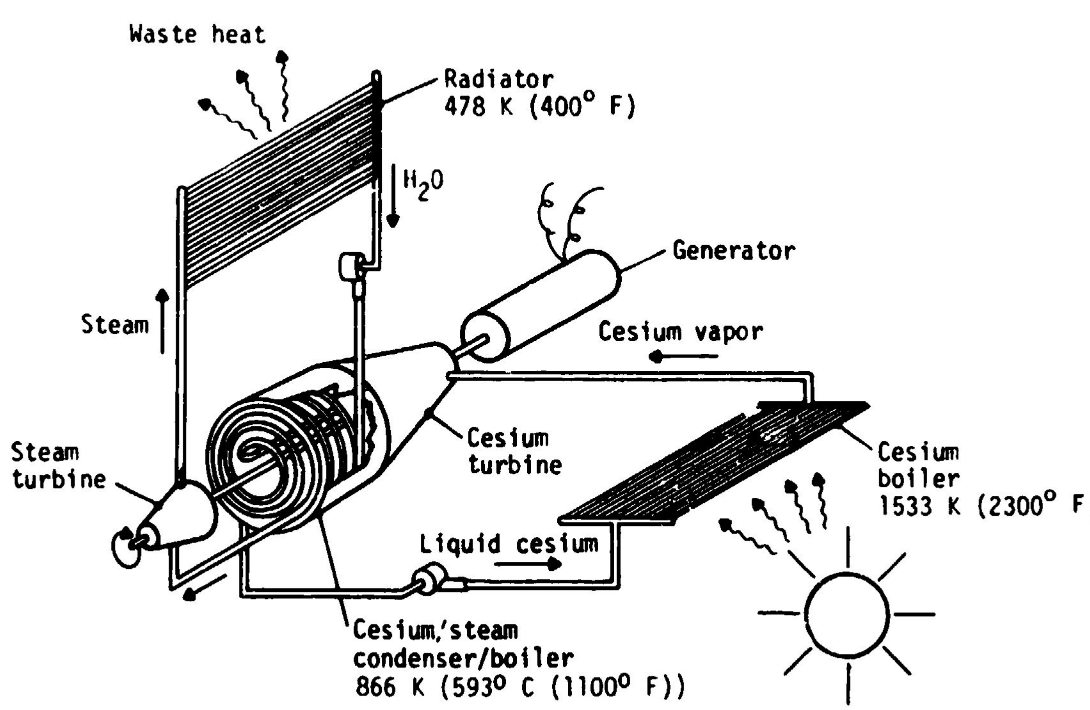

Figure III-8.- Cesium/steam Rankine cycle, 5 gigawatts.

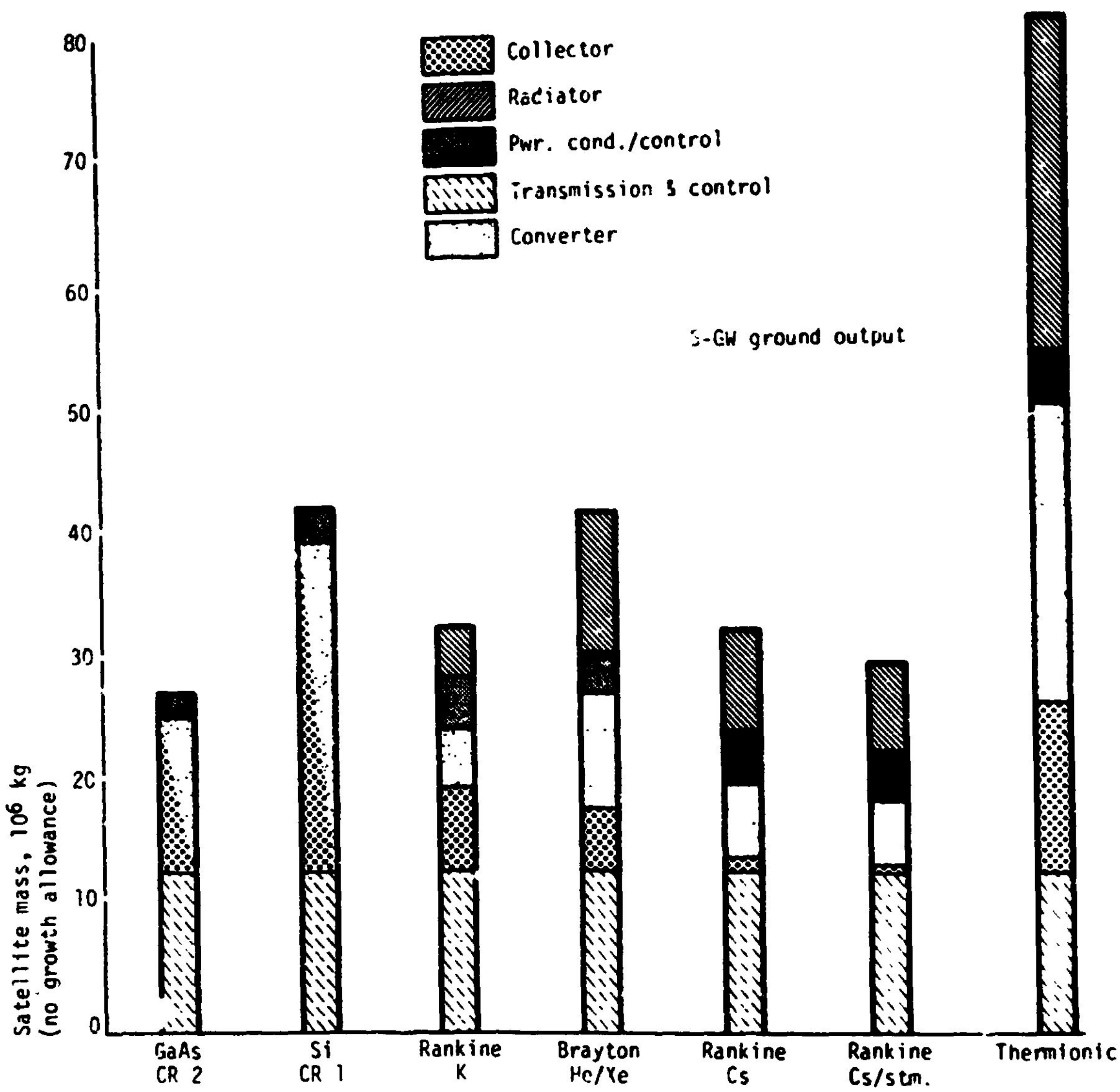

Figure III-9.- Energy conversion comparison, SPS mass.

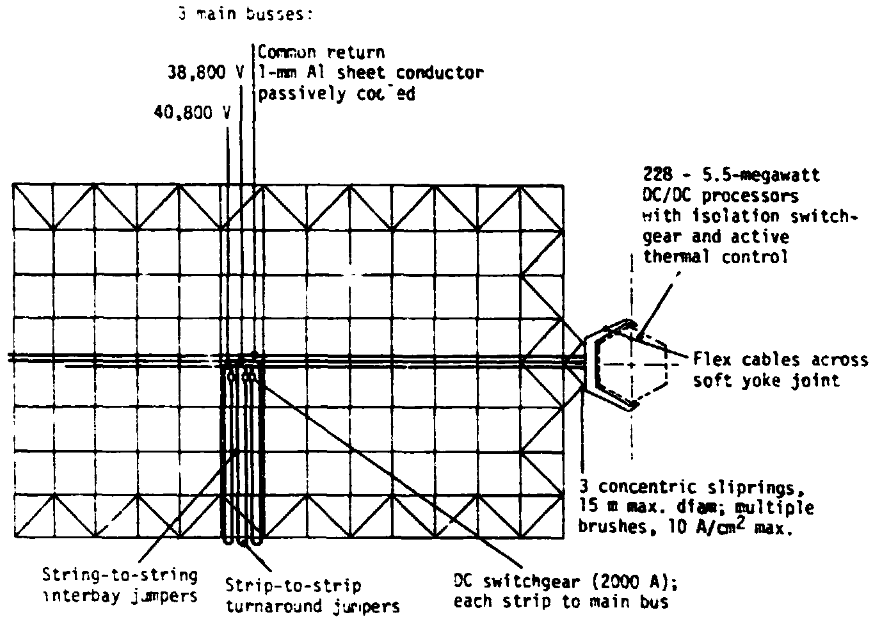

Figure III-10.- SPS power distribution.

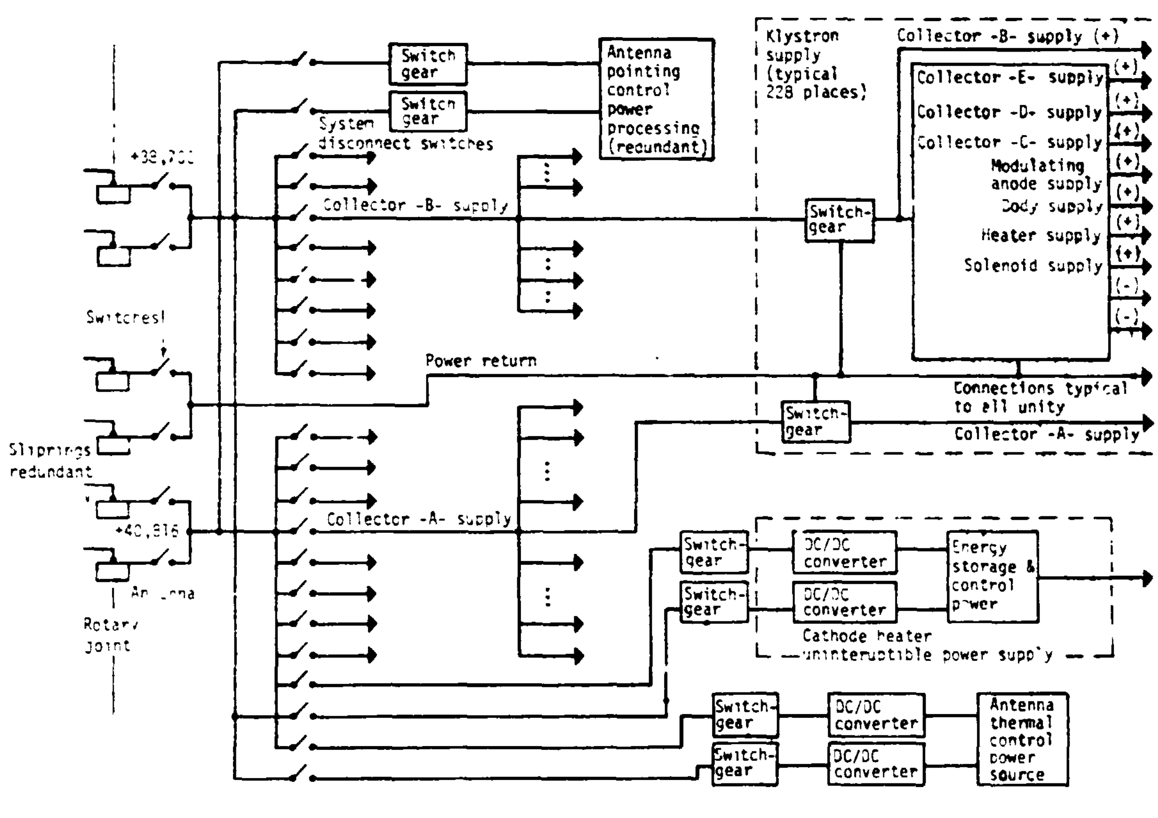

Figure III-11.- Power distribution system block diagram.

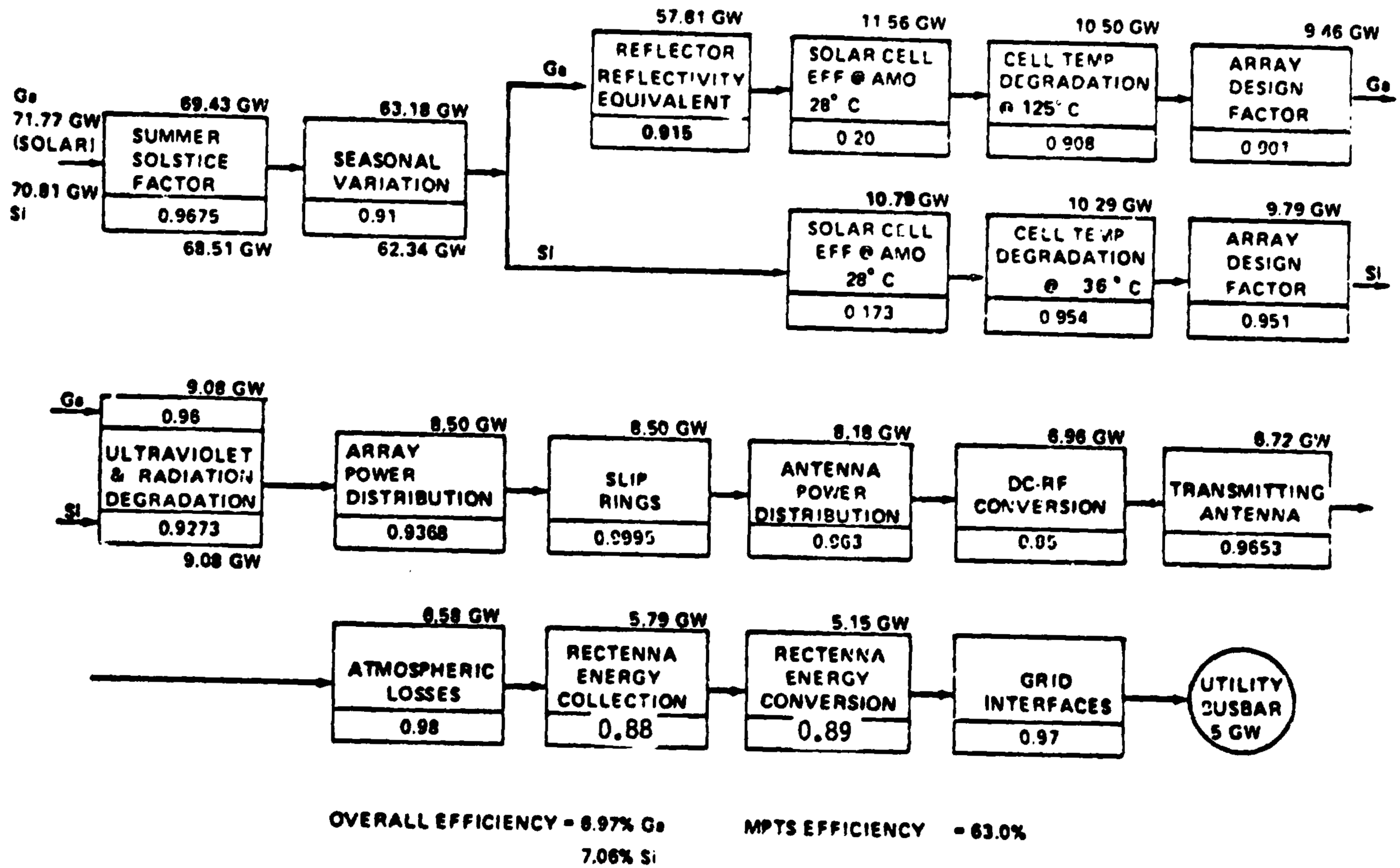

Figure III-12.- SPS efficiency chain (GaAlAs (CR2) and Si (CR1)).

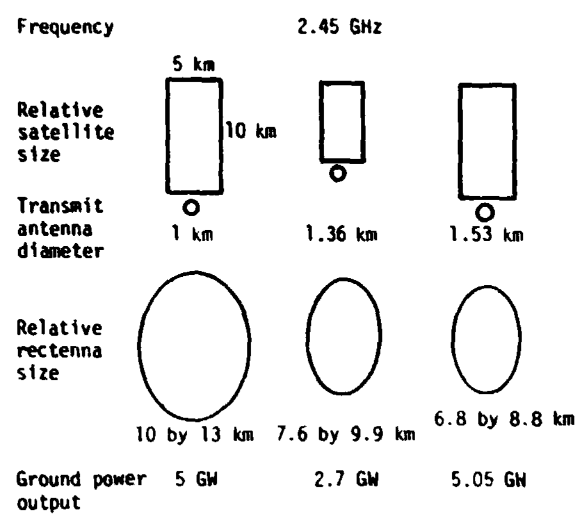

Figure III-13.- System sizing study results - 2.45 gigahertz (ref. 11).

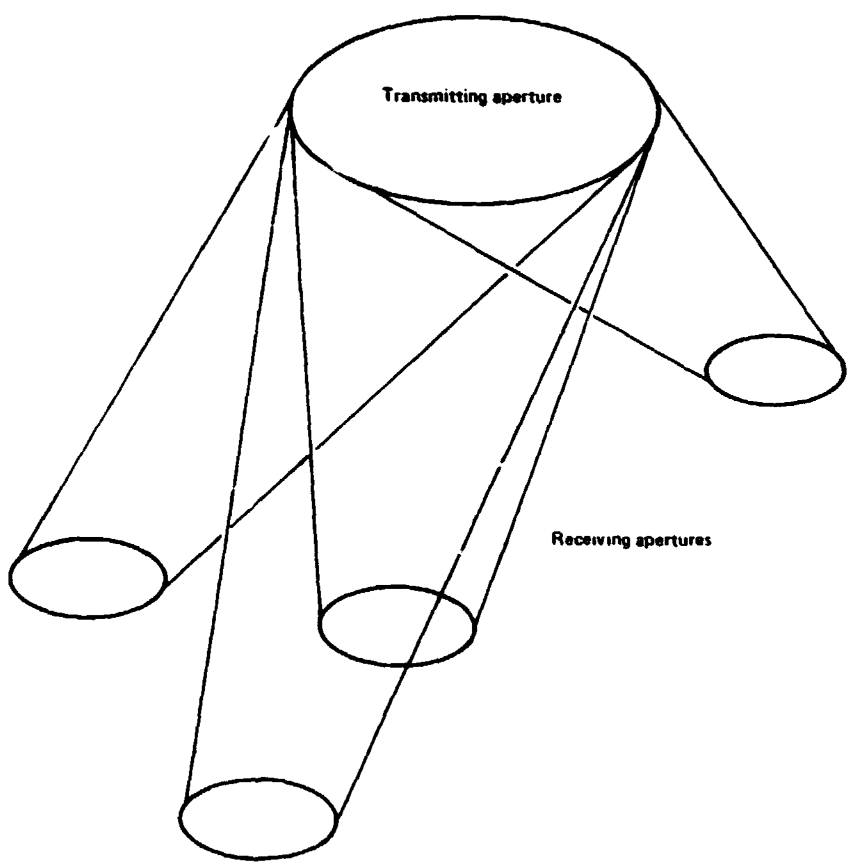

Figure III-14.- Diagram illustrating illumination of several spots from a single aperture.

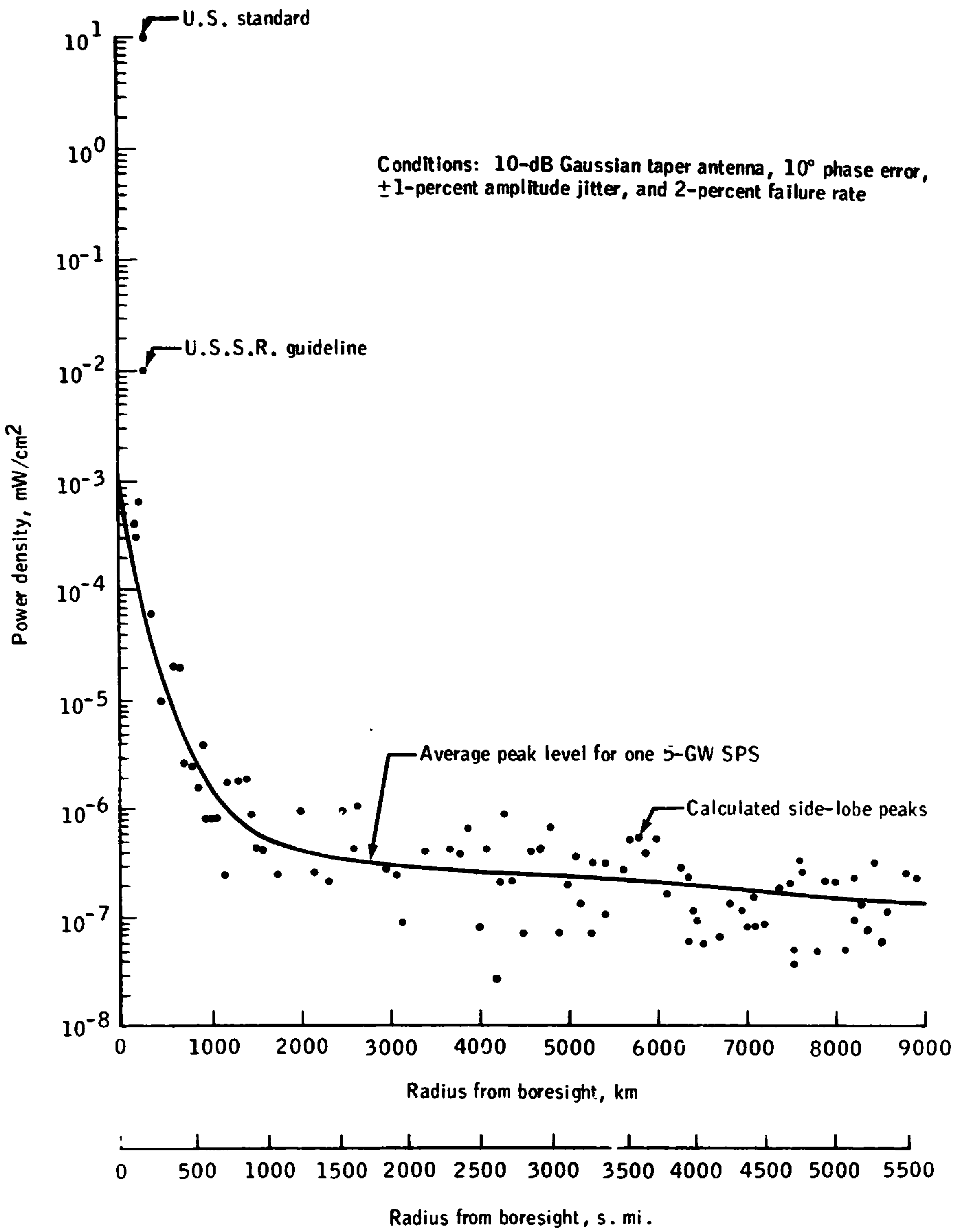

Figure III-15.- Peak power density levels as a function of range from rectenna.

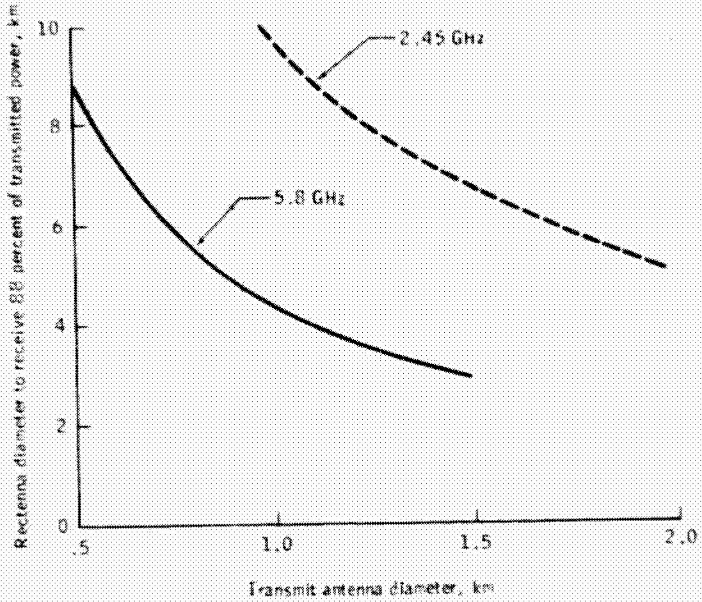

Figure III-16.- Antenna/rectenna sizing summary.

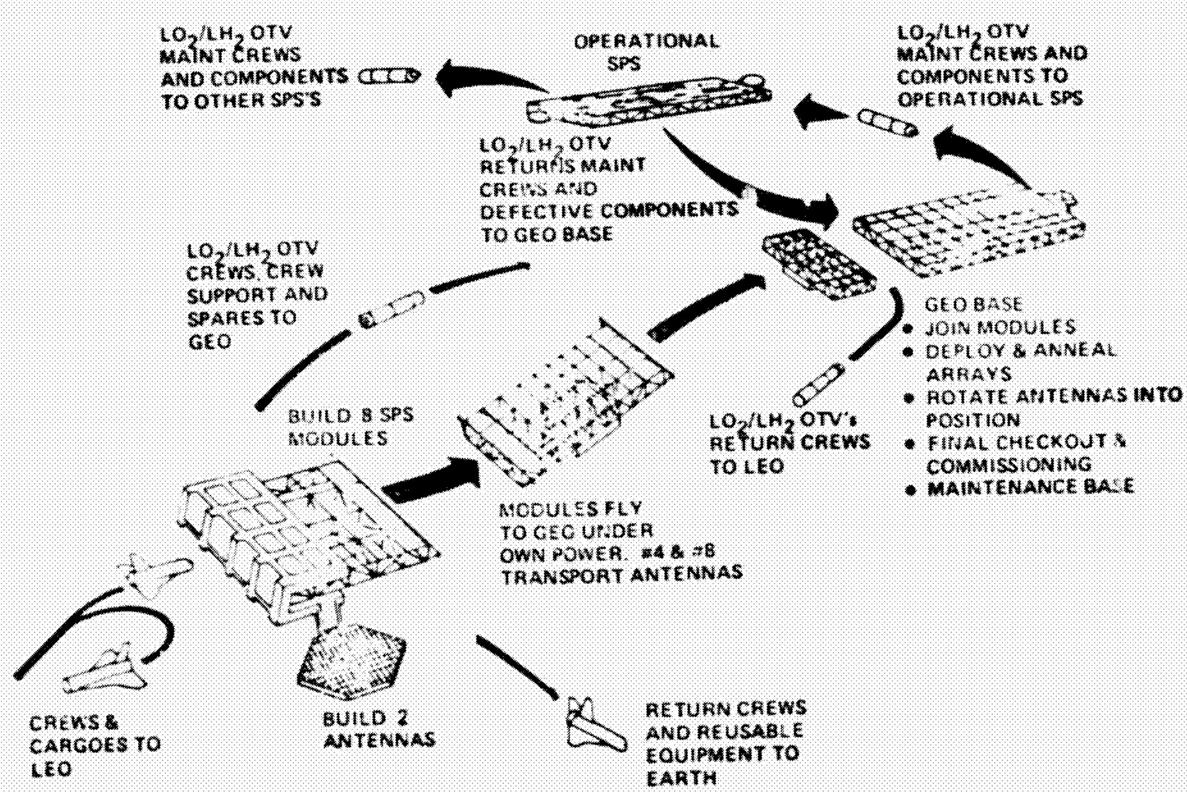

Figure III-17.- Integrated space operations (LEO construction).

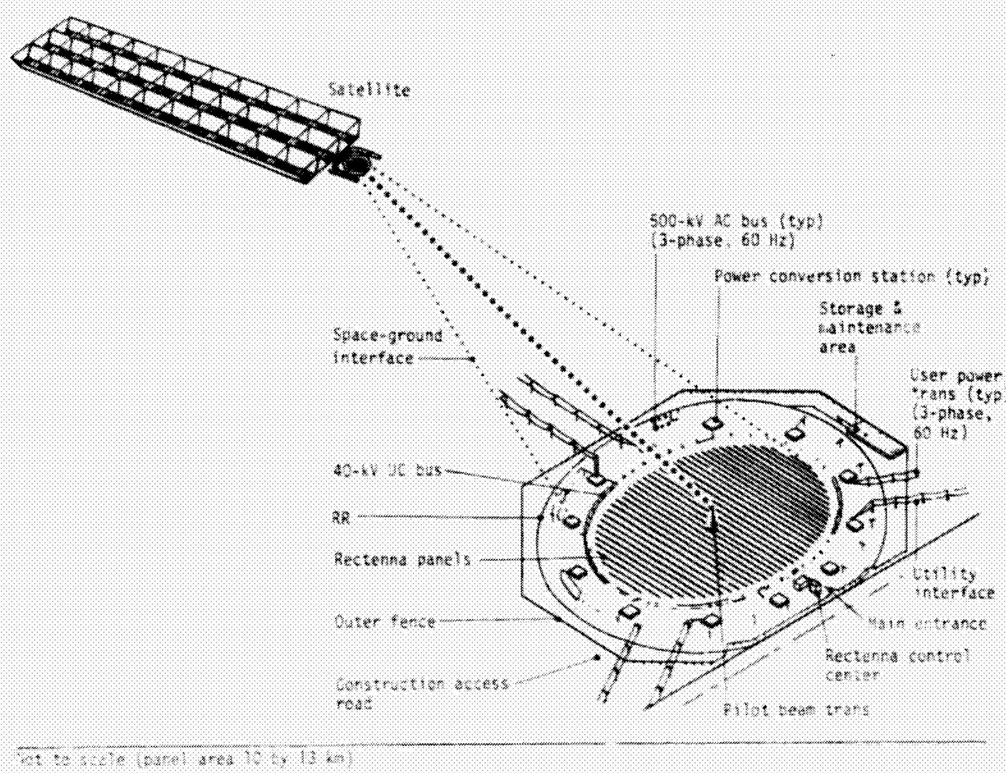

Figure III-18.- SPS system showing rectenna details.

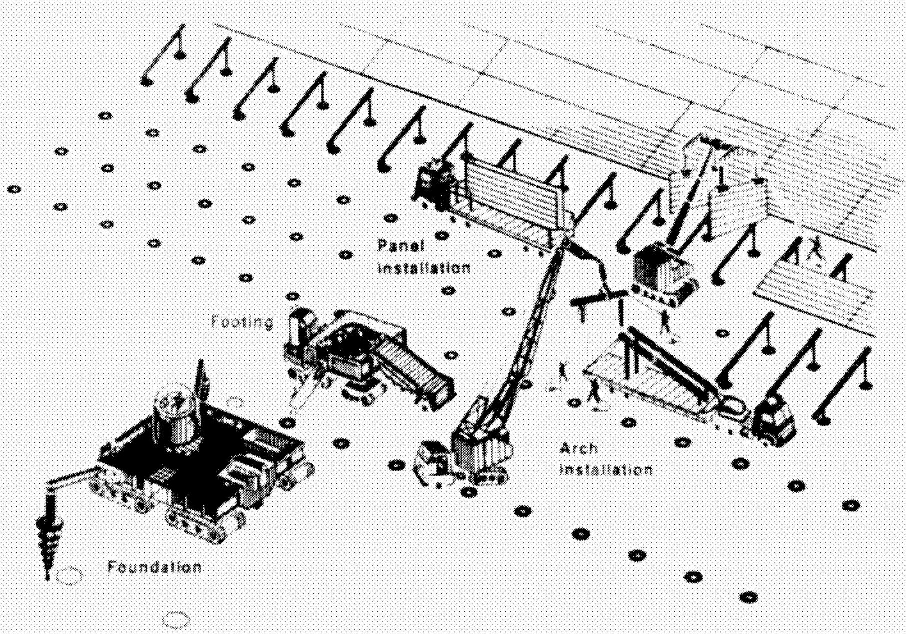

Figure III-19.- Rectenna construction concept.

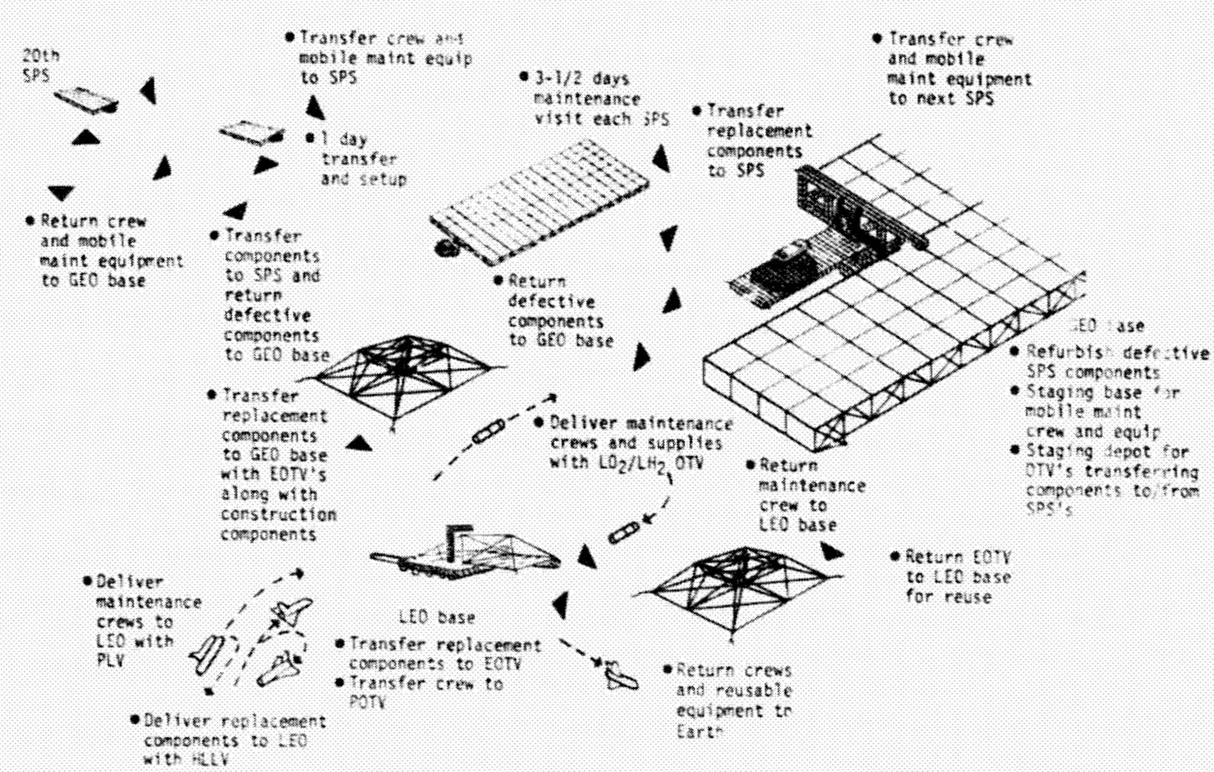

Figure III-20.- Integrated maintenance mission concept.

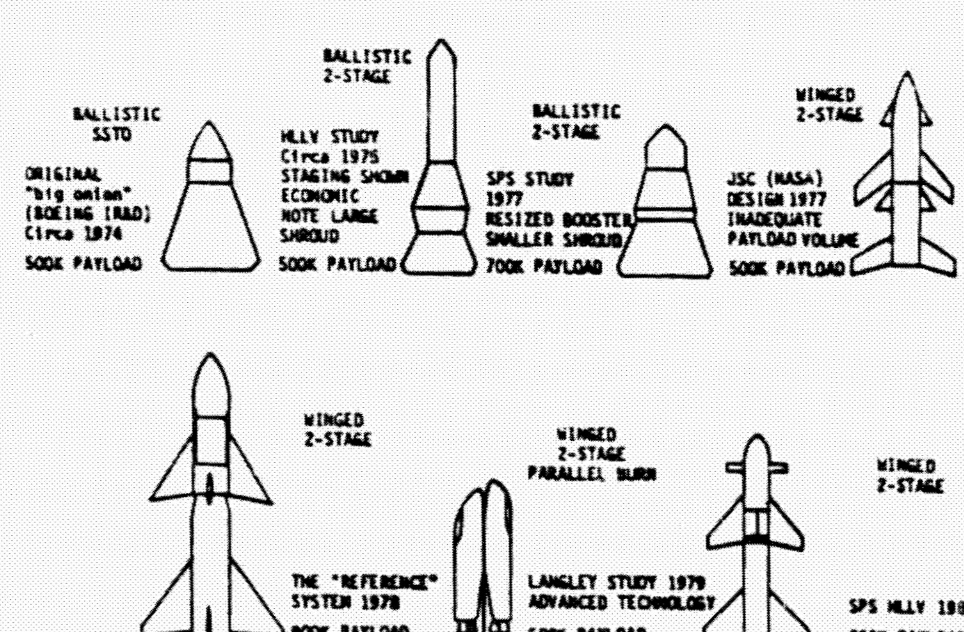

Figure III-21.- SPS launch vehicle concept evolution.

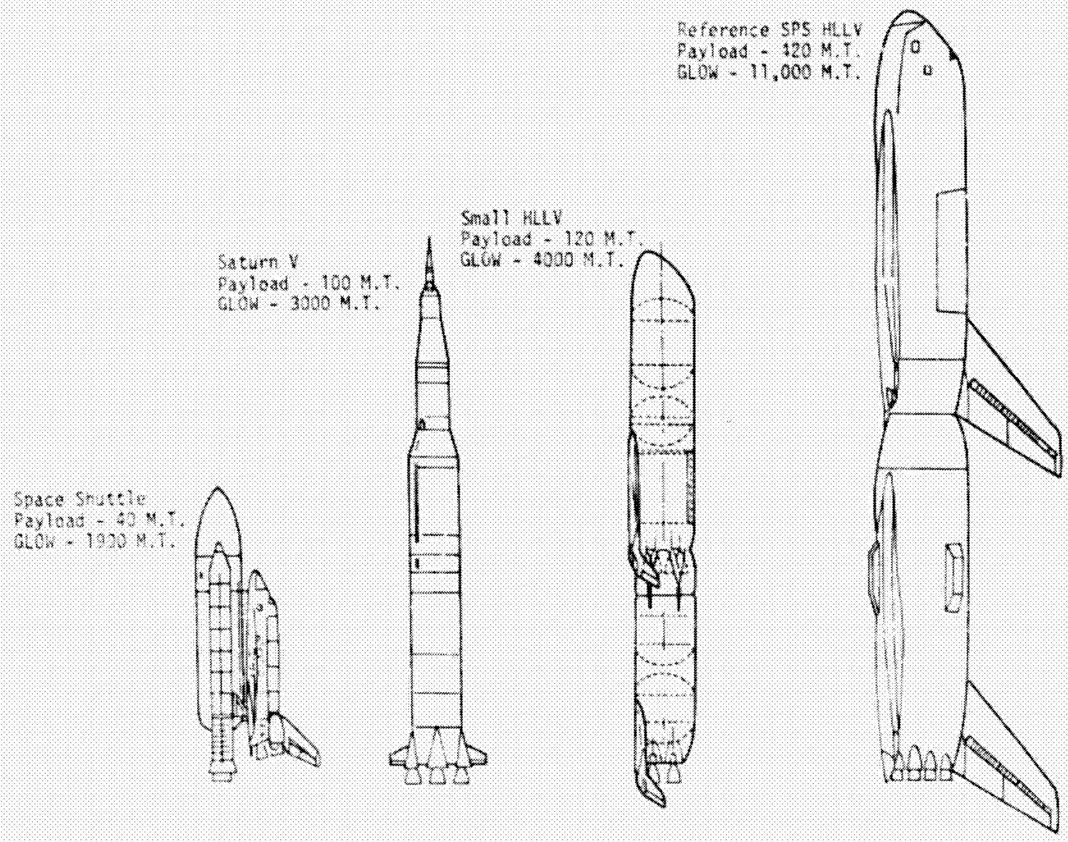

Figure III-22.- Launch systems size comparison.

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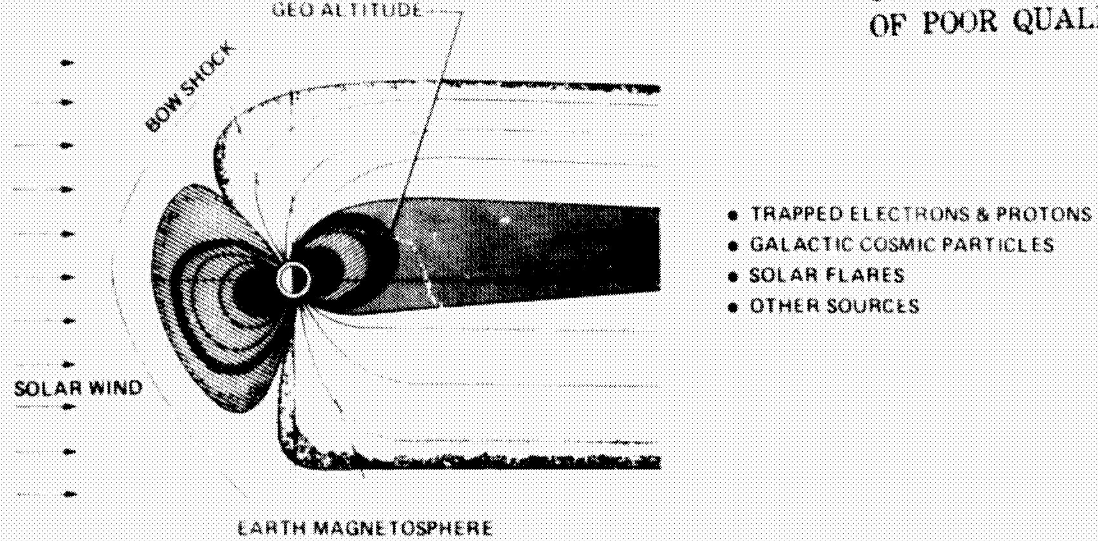

Figure III-23.- SPS GEO radiation sources.

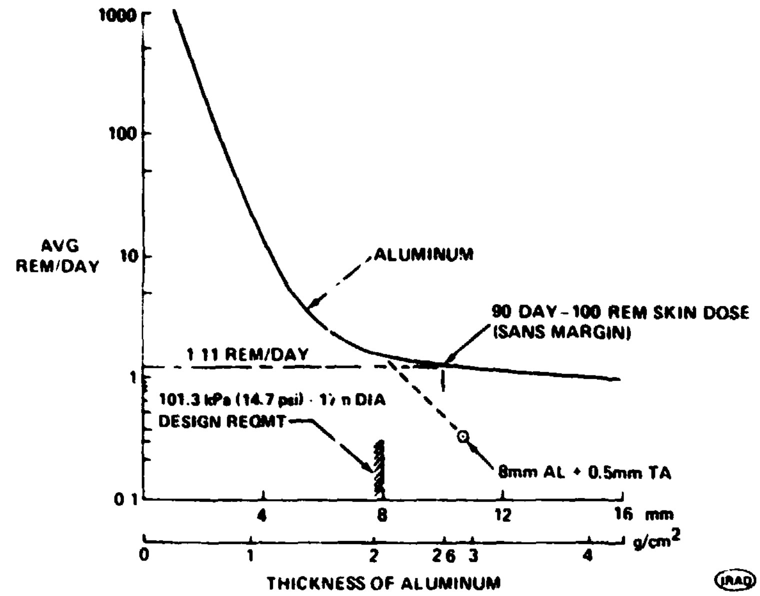

Figure III-24.- Shielding thickness for GEO trapped electrons plus bremsstrahlung (270° E longitude).

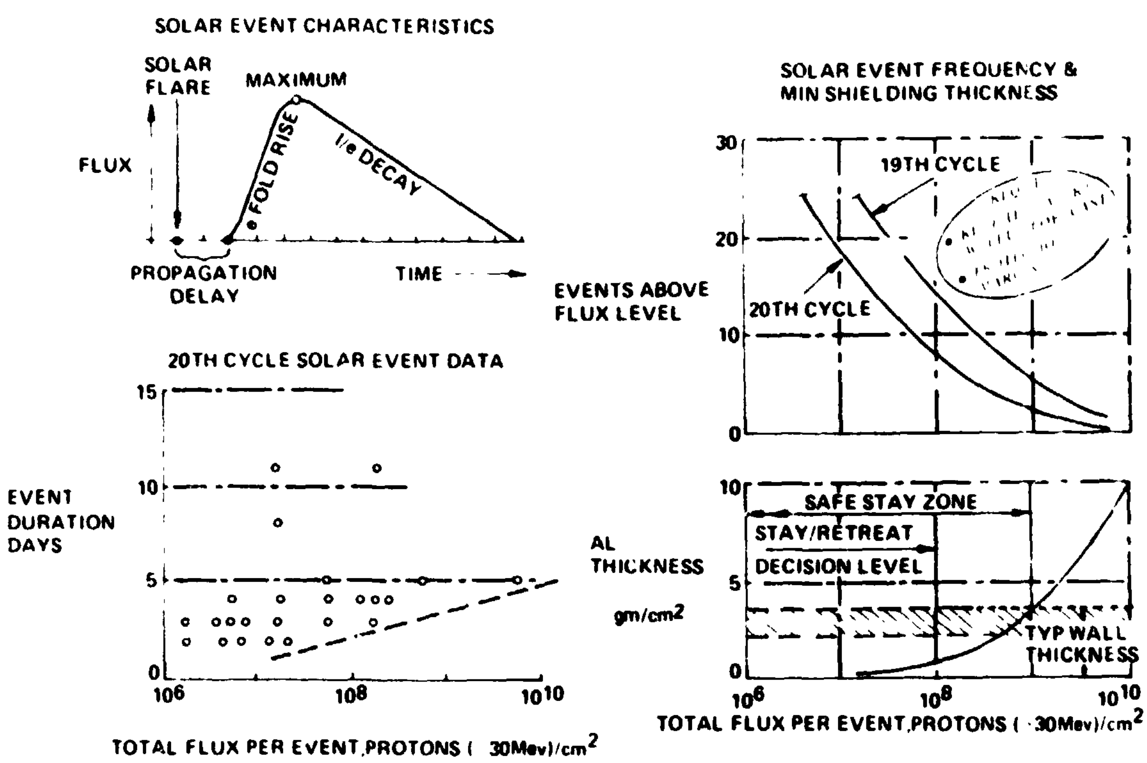

Figure III-25.- Solar flare radiation protection requirements.

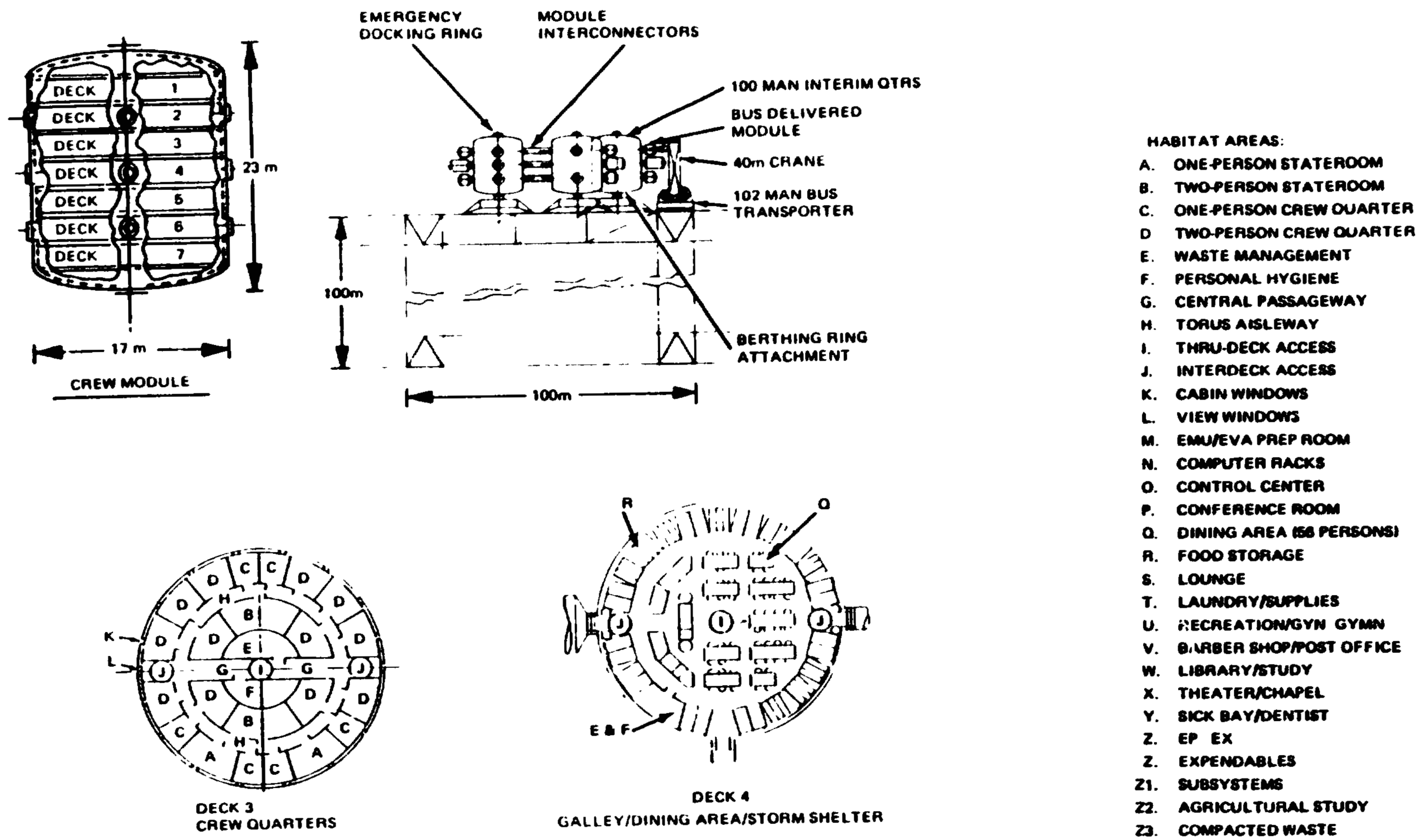

Figure III-26.- Crew habitat modules (refs. 12c and 16b).

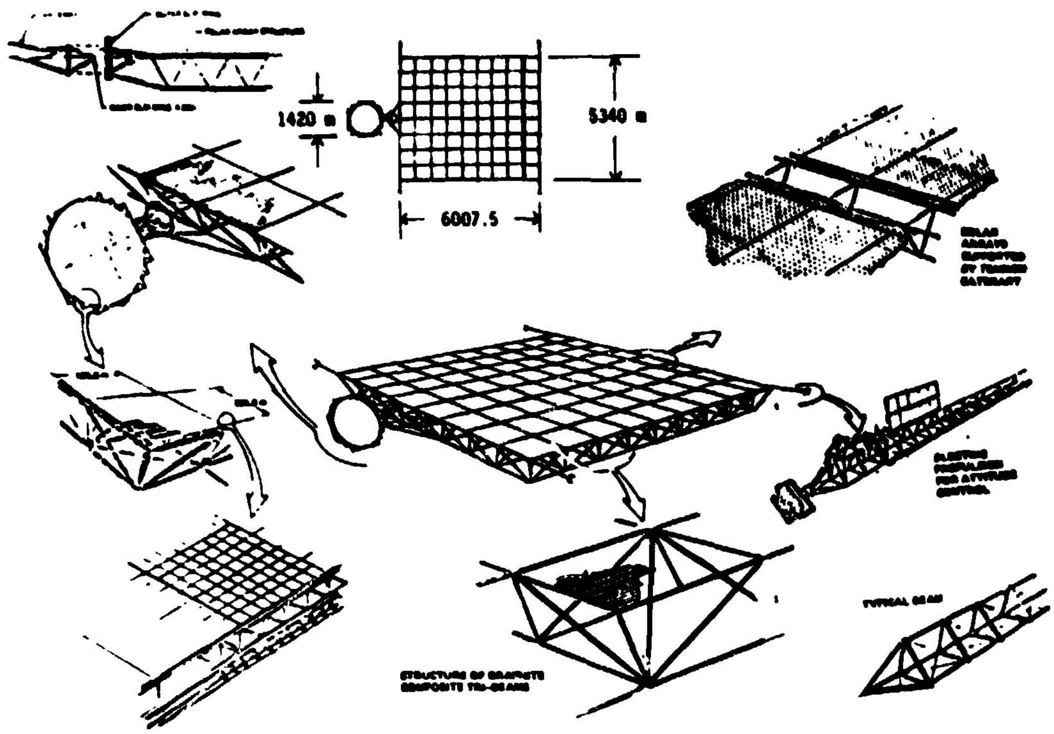

Figure III-27.- 2.5-gigawatt solid-state SPS configuration.

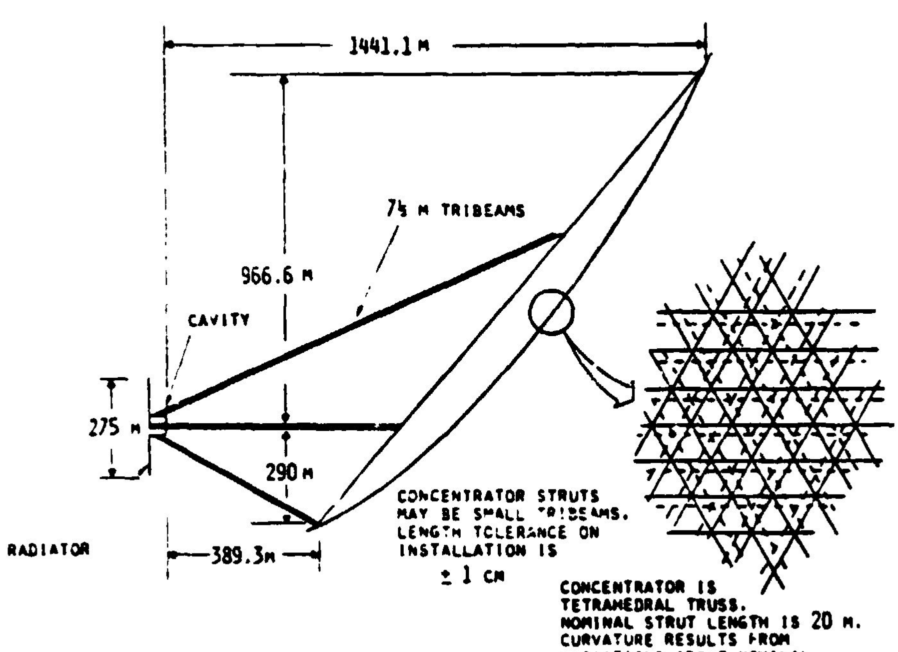

Figure III-28.- Indirect optically pumped laser SPS general arrangement.

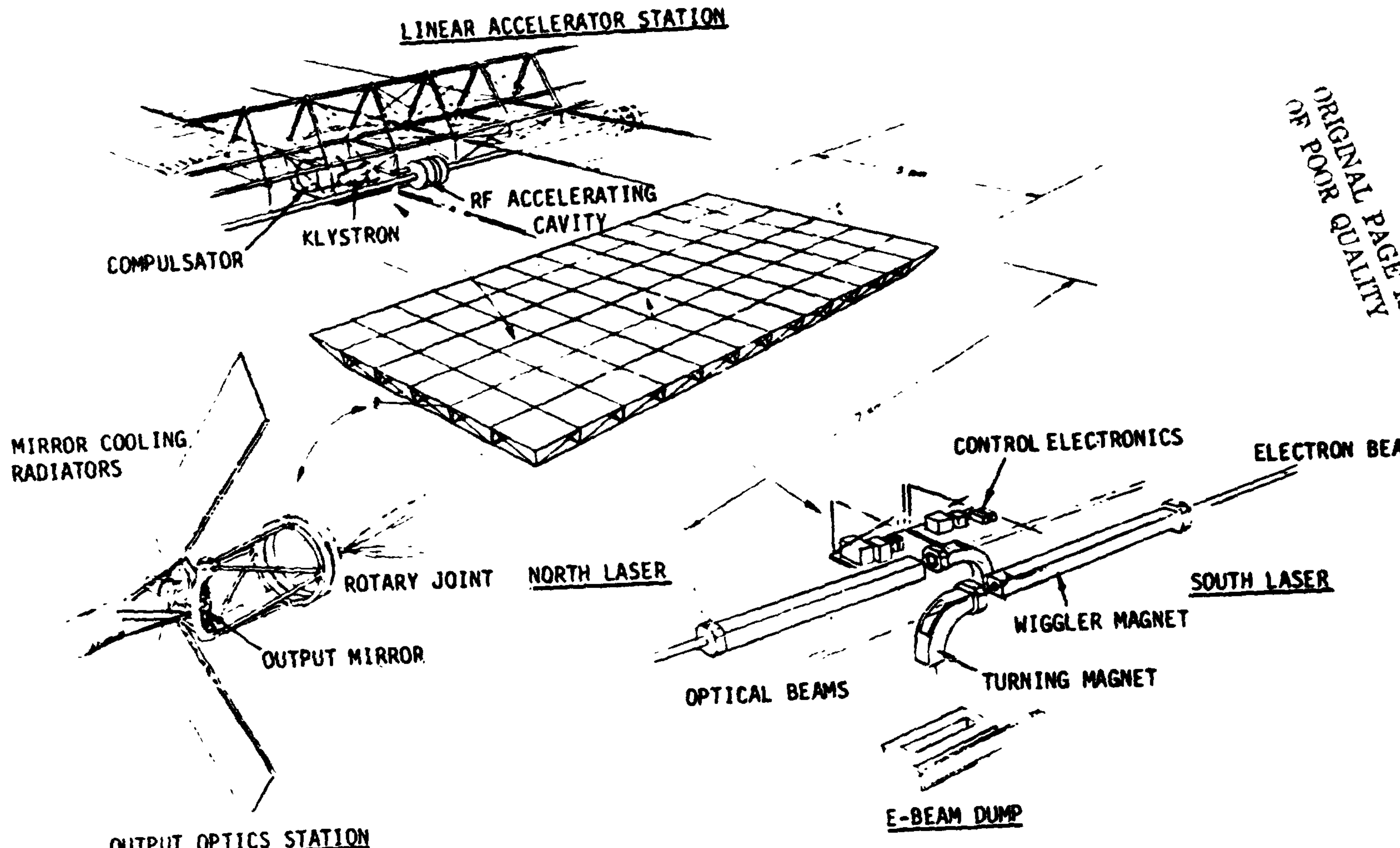

Figure III-29.- 1-gigawatt single-pass free-electron laser SPS.

IV. COSTS

A. GENERAL ANALYSIS

Because costs are the final determinant in the acceptance of an energy system, the systems definition effort has attempted to derive cost models and to estimate costs for the reference system. The cost models have been used to assess the value of alternative approaches and to provide the guidance to determine the important factors in a cost sense

The estimates were based on the scenario defined in the reference system report (ref. 2) and the production rates associated with that scenario. Detailed cost data may be found in references 7c and 16b. Subsequent sections of this report contain discussions of cost estimates within particular areas of technology.

The cost of a 5-gigawatt silicon reference system satellite, based on the average unit cost of 60 satellites, was determined to be $5 billion (1977 dollars). Space transportation, the cost of transporting the materials and personnel to construct a 5-gigawatt satellite in geosynchronous orbit, was $2.8 billion. The ground receiving station, including rf-to-dc conversion, power distribution and conditioning, grid interface, structure, and land acquisition, was $2.2 billion. Assembly and support during construction, based on crew salaries and resupply at LEO and GEO bases, was $840 million. Program management and integration was estimated to be $430 million. The sum of these costs is $11.3 billion for each 5-gigawatt system, or $2260/kW (fig. I-6).

In addition to the cost of acquiring and building each power system, there are costs incurred in developing the industrial capability to produce hardware, the launch facilities, the fleets of vehicles for the transportation system, and the space bases at low Earth orbit and at geosynchronous orbit. An estimate has been made for these nonrecurring costs under the assumption that an SPS program would bear the full burden and that there are no other activities which would serve to develop the capabilities required in SPS. Although this assumption may not be realistic, the cost estimates thereby created give the maximum burden to SPS development.

The nonrecurring costs were assembled for several program phases: research, engineering, demonstration, and investment. The distribution of costs by phase could vary depending on the exact goals of each phase. This scenario is based on an evolutionary path leading to the construction of the first SPS. During the various phases, hardware capability and design, development, test, and evaluation (DDT&E) for SPS program parts are evolved such that the ability to construct an SPS in geosynchronous orbit would exist at the end of the investment phase. Figure IV-1 illustrates the distribution by phase of the total front-end cost of $102.4 billion, which includes the cost of the first SPS. The distribution of this cost over a 20-year period is shown in figure IV-2. It should be noted that the first two phases - research and engineering - are activities that probably would have to be conducted with all funding supplied by government. This amount is approximately $25 billion for the activities that should lead to a clear-cut determination of feasibility

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and economic viability. The subsequent phase - demonstration and implementation - would therefore be accomplished (all or in major part) with private investments; otherwise, SPS would not be pursued.

Maintenance costs per satellite system are depicted in figure IV-3. Transportation cost represents more than half of the total. More than 80 percent of the transportation cost is for personnel and their supplies, and approximately 20 percent is for transportation of replacement materials. The next largest item, $39 million/yr, is replacement parts for klystrons, dc-dc converters, and other satellite components.

All the costs given previously are for the silicon reference system. Costs for the gallium arsenide reference system are similar. Because of its lower mass, the GaAs system transportation cost is lower. The solar cell costs, however, are higher, and the total cost per system is estimated at $13.8 billion (ref. 7c). Because of slight differences in cost-estimating methods, this figure is not directly comparable to the $11.3 billion given previously for the silicon system. Reference 38 provides a summary of system costs for gallium arsenide solar cell options, alternate microwave transmission systems (klystron, magnetron, solid state), and ground power output.

The cost estimates are referenced to 1979 dollars and are based on a composite of cost-estimating relationships developed by NASA and Rockwell International. The estimates are separated into DDT&E, theoretical first unit (TFU), average investment per satellite, and operations. The DDT&E covers all costs through the construction and operation of the pilot plant. The TFU costs cover all capital expenditures to build the first commercial unit, including the cost of all construction material for the satellite and ground receiving station, construction costs, transportation costs, management and integration costs as well as the cost of the construction fixture and the space transportation fleet needed to provide transportation for the first unit. The average investment cost per satellite is the average cost of building a sufficient number of units to provide 300 gigawatts of power. The number of satellites varies, depending on the system characteristics. Construction fixture costs and transportation fleet costs and their maintenance are amortized equally over all satellites. Operations costs include all costs related to system operations and maintenance, including replacement of capital investment.

The DDT&E and TFU costs did not vary significantly from one concept to another. The reference (klystron) concept had a DDT&E cost estimate of $33.6 billion and a TFU cost of $53.6 billion. The highest values were $35.0 billion DDT&E and $56.0 billion TFU cost for the solid-state, dual end-mounted antenna concept.

Major differences in cost did occur for the average unit. The estimates are shown in figure IV-4 for all the GaAs concepts. Figure IV-4 shows the costs in terms of the installation cost per kilowatt of power at the utility interface. The highest value is $3670/kW for the GaAs solid-state sandwich concept; the lowest value is $2310/kW for the multibandgap (MBG) magnetron concept. The Rockwell reference concept (GaAs solar array and klystron dc/rf converters) has a cost of $3020/kW. Figure IV-4 also illustrates the distribution of the costs across the various cost elements.

B. MICROWAVE SYSTEM COST SENSITIVITIES ANALYSIS

Changes in system efficiencies will have economic as well as environmental impacts on overall SPS performance. From a systems viewpoint, it is important to ascertain the benefits (or losses) derived from a small improvement (or degradation) in the performance of each subsystem. For example, is it economical to spend $50 million to improve the dc-rf conversion efficiency of the klystrons by 1 percent? The SPS efficiency chain from the solar array output in the satellite antenna to the utility grid busbar at the ground is shown in figure IV-5.

In terms of economics, there are two types of system losses.

1. Inefficiencies that can be compensated for by simply increasing the amount of power generated by the solar array

2. Degradations (or inefficiencies) that cannot be made up by increasing the solar array size because of system limitations - An example is the dipole/diode rf-dc conversion loss in the rectenna when the system is operating at the maximum power density limit in the ionosphere.

The economic impact of a type 1 degradation is less than that of a type 2 loss as shown subsequently. The cost and mass statements for the subsystems within the reference satellite that are dependent on solar array power are shown in table IV-1. These cost numbers may be summarized into an overall SPS system cost. The overall cost per 5-gigawatt satellite is $12 432 million with a resulting electricity cost of 1.31¢/MJ (47 mills/kWh). The differential cost per 1-percent increase in solar array power to compensate for losses in the microwave system is, to a first-order approximation, $56.4 million as obtained by summing the last column. This is the economic impact of a type 1 degradation.

The type 2 degradations that result in a loss of electrical power to the utility grid are obtained by multiplying the electricity rate times the power delivered over the 30-year lifetime of the satellite.

$$\begin{aligned}\text{Revenue loss} &= \$0.047/\text{kWh} \times 8760\ \text{hr/yr} \times 30\ \text{yr} \\ &\quad \times 50\,000\ \text{kW (1 percent of 5 GW)} \\ &= \$617\ \text{million}\end{aligned}$$

In summarizing, the economic costs of a 1-percent reduction in power are, for type 1 (compensated for by an increase in solar array output), $56 million; for type 2 (no compensation), $617 million.

The relative importance of the microwave subsystem losses depends on where they occur in the efficiency chain. That is, a 1-watt type 1 loss at the rectenn has a greater economic impact than a similar loss in the klystron tube. The microwave subsystem performance impact based on a 10-percent variation in each loss is illustrated in figure IV-6. The rectenna conversion efficiency has the greatest impact because of the premise that the system is operating at the ionospheric limit. If the rectenna losses could be compensated for by increasing the transmit power, the economic impact would decrease by an order of magnitude as shown. This also shows the importance of being able to predict the losses over the 30-year lifetime of the satellite.

TABLE IV-1.- COST AND MASS SUMMARY FOR REFERENCE SATELLITE SUBSYSTEMS DEPENDENT ON SOLAR ARRAY POWER

Subsystem	Reference system		Differential impact for a 1-percent increase in solar array power	
	Mass, t	Cost, $	Mass, t	Capital cost, $
Solar array				
Structure	4 654	448 × 10^6	47	4.5 × 10^6
Solar cell blankets	21 145	1988	211	20
dc power distribution	1 246	150	12	1.5
Maintenance	621	274	6	2.7
Total	27 666	2860	276	28.7
Power transmission - klystrons and thermal control	7 007	477	70	4.8
Satellite total[a]	50 984	4946	346	33.5
Transportation				
EOTV	--	652	--	6.5
PLV[b]	--	286	--	2.8
POTV[c]	--	14	--	.1
HLLV	--	2167	--	10.5
Total	--	3119	--	19.9
Construction operations				
GEO	--	648	--	1.5
LEO	--	313	--	1.5
Total	--	961	--	3.0

[a]Includes rotary joint, antenna structure, waveguides, subarray structure, phase distribution, mechanical pointing, information management, altitude control, communications, and 22 percent mass growth not directly related to solar array output power.

[b]PLV = personnel launch vehicle.

[c]POTV = personnel orbital transfer vehicle.

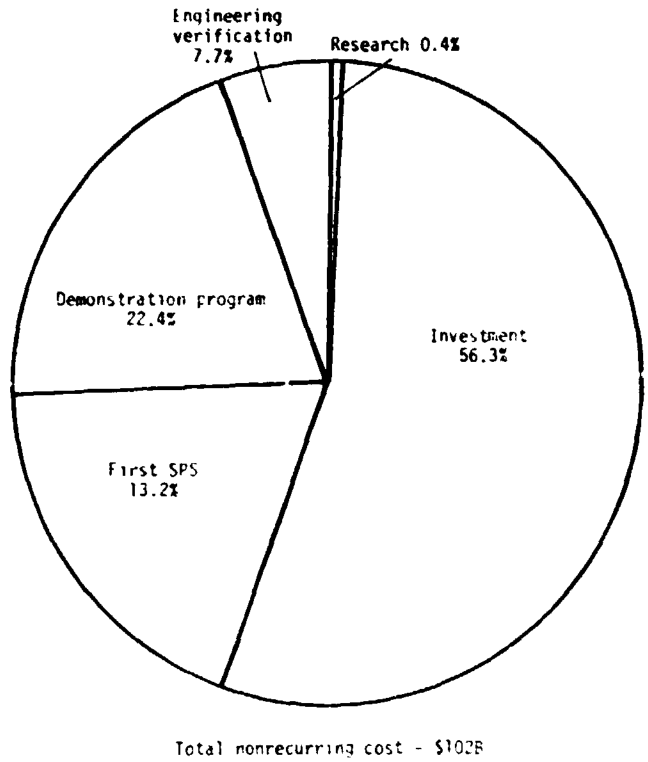


Figure IV-1.- SPS nonrecurring costs.

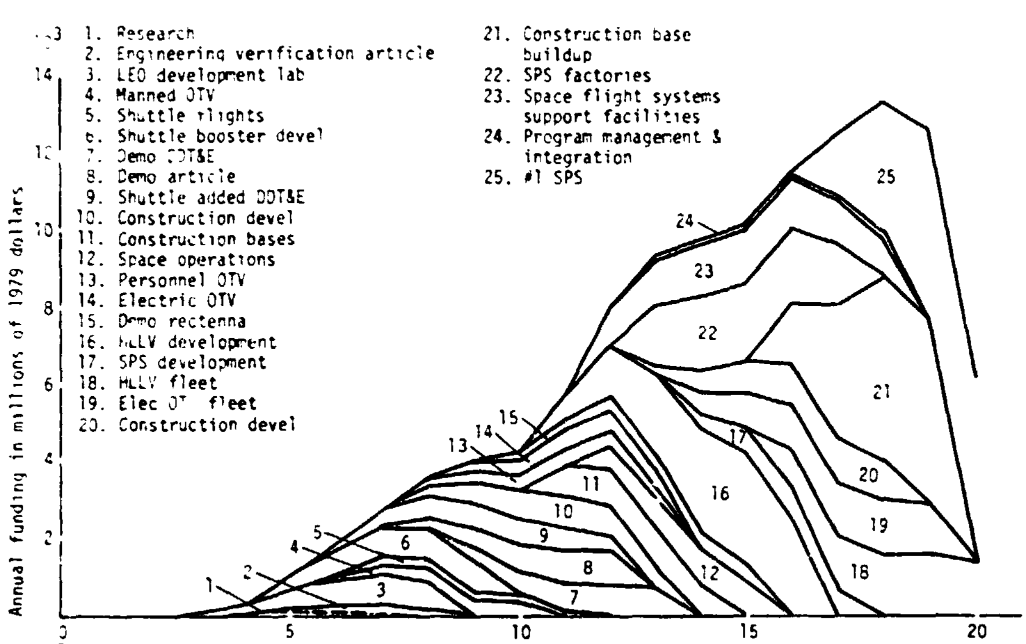
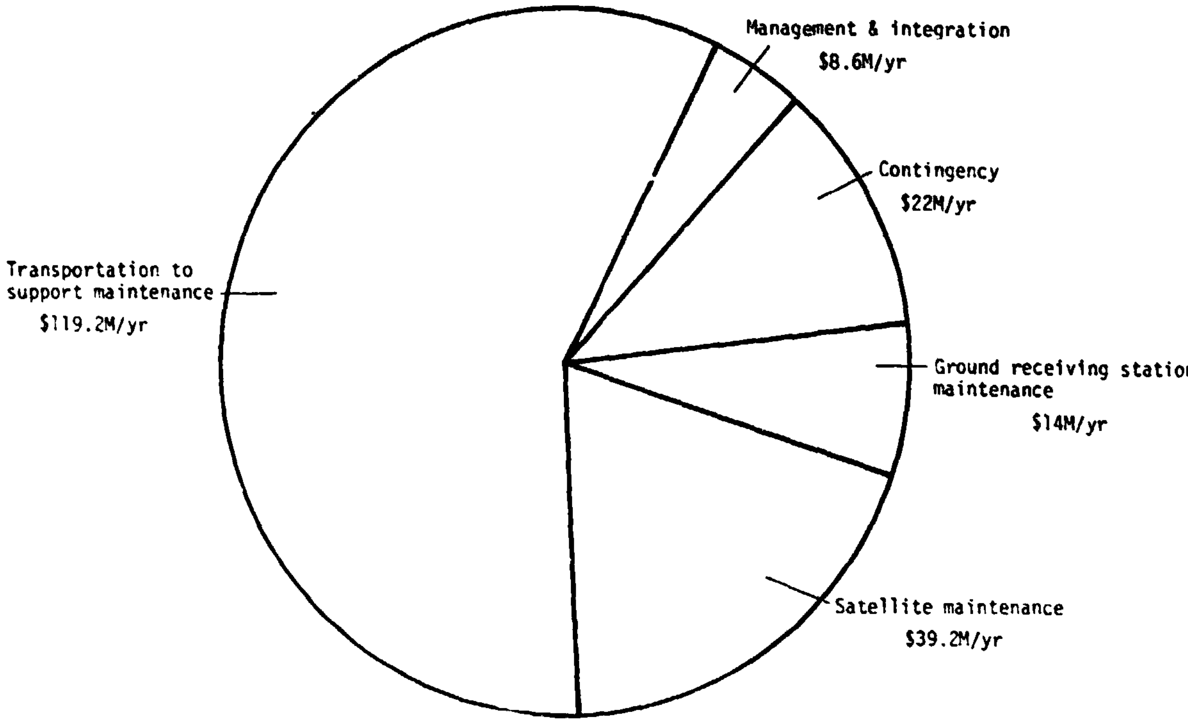


Figure IV-2.- SPS total program costs by year.



Annual maintenance expense - $203.4M/5-GW system

Figure IV-3.- Maintenance cost.

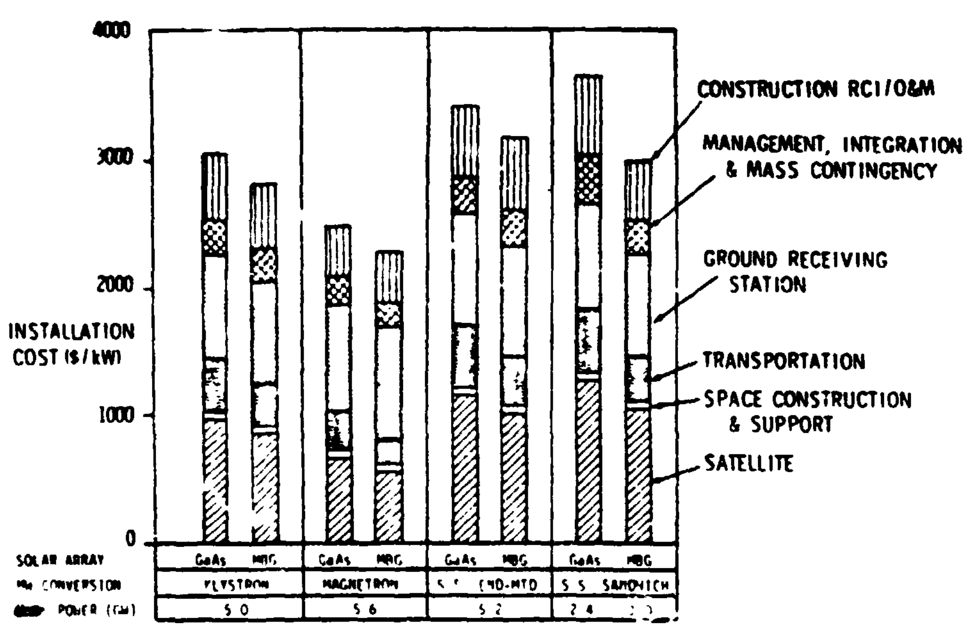


Figure IV-4.- Installation cost comparisons.

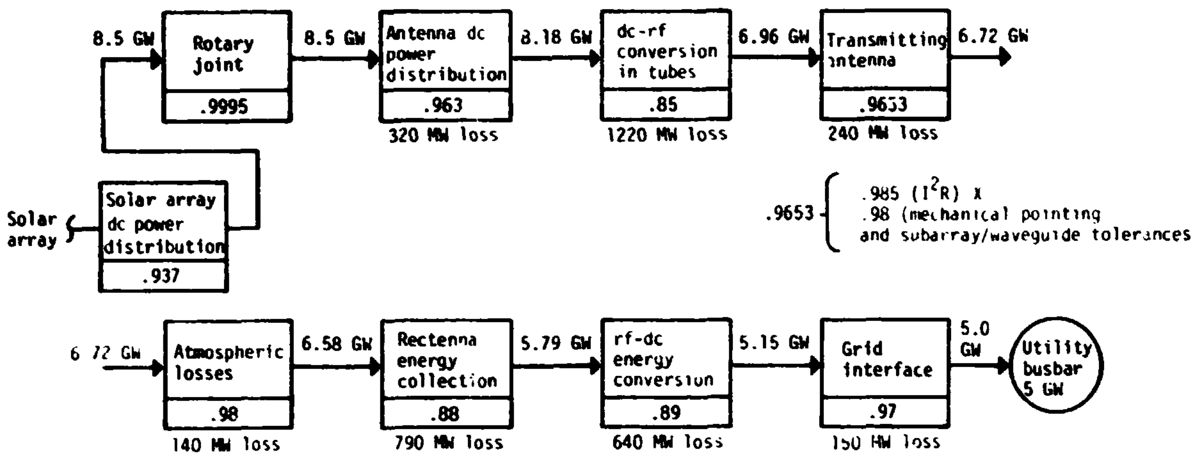


Figure IV-5.- SPS efficiency chain.

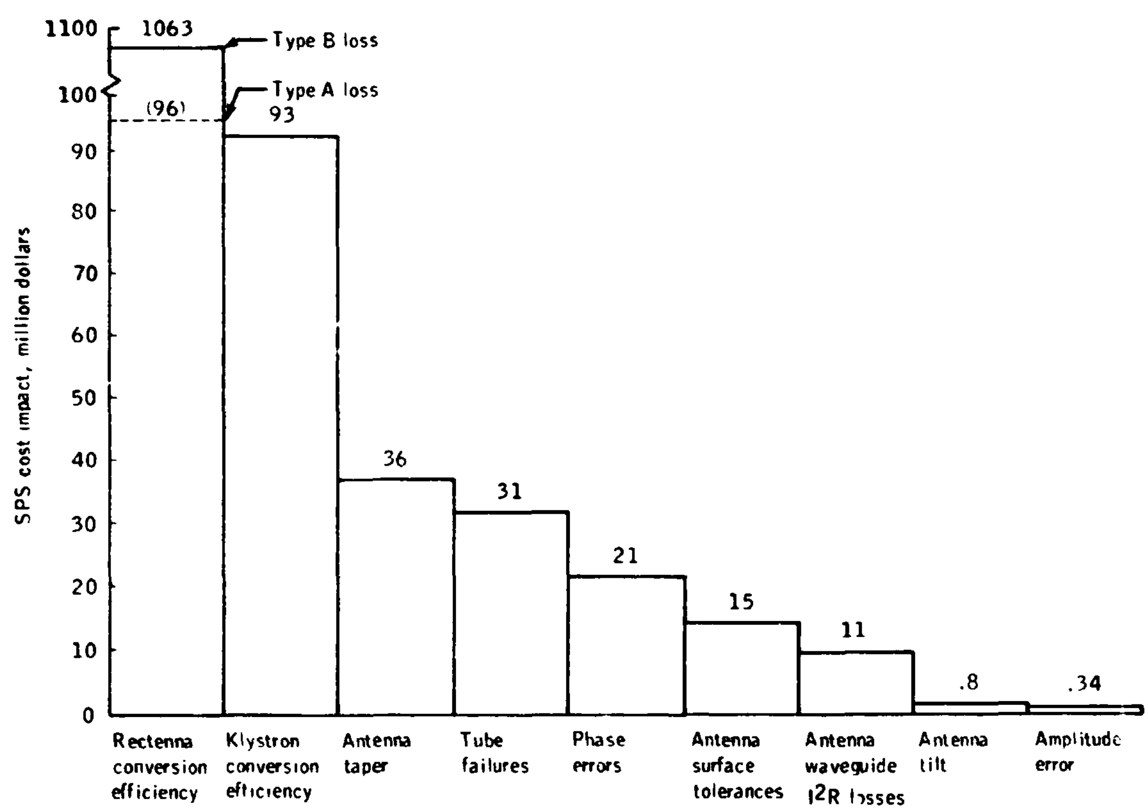


Figure IV-6.- Summary of cost sensitivities for a 10-percent change in subsystem losses. Antenna tilt is doubled from 1 to 2 arc-minutes; all other subsystems have a 10-percent change.

V. SYSTEMS ANALYSIS AND PLANNING

As a part of the system definition activity, a number of alternative technology and system development plans were developed and analyzed. In these studies, the importance of a phased development program (wherein each phase builds on the results of preceding phases and wherein each phase would have specific goals and objectives) was recognized. Typical phases that might be included in such an evolutionary plan are concept identification and preliminary studies, a concept evaluation program (represented by the CDEP effort), an exploratory research phase to answer critical questions through laboratory development and testing, and a series of space technology projects to develop operational techniques and to demonstrate key elements of the system. The combined results of these four phases of activity would provide the necessary information on which to base a decision for the commitment to full-scale system development and commercial operations.

In response to a requirement of the CDEP that a plan for future activities in SPS be developed, a Ground-Based Exploratory Development plan was produced. The GBED plan describes one approach or option for addressing critical technology issues (questions) in SPS as defined largely through an evaluation of the reference system.

The GBED plan is a program having the goal of resolving major remaining technological questions in 5 or 6 years. Although the 1979 GBED plan does not represent a preferred program option for the future, the planning effort was useful in providing a summary of technical issues in SPS and in defining initial steps for addressing these issues.

The objectives of the GBED effort were as follows.

A. To resolve key technology issues that affect the decision on whether to proceed to an SPS technology verification program - This objective would be accomplished by conducting carefully planned, critical experiments in ground laboratories and in space as necessary.

B. To support the environmental, societal, and comparative assessments by providing analytical and experimental data as required

C. To define preferred overall system concepts, including alternate compatible subsystems

D. To define the plans and projects that would be required in a post-GBED technology verification phase

For GBED planning purposes, seven major technical areas were identified. These areas are discussed in the following subsections.

A. SYSTEM DEFINITION AND PLANNING

The system definition and planning area consists of system design, analysis, and planning functions. Key questions to be resolved in this area are the following.

1. What are the characteristics of alternate SPS concepts (lasers, thermal conversion, solid-state microwave) and what are their advantages and disadvantages?

2. What are the available system responses to the results of specific SPS environmental/societal/comparative assessments?

3. What are the system effects and modifications resulting from the SPS exploratory development programs and from other technology development efforts?

4. What are the benefits of emerging technologies to the SPS concept?

5. What is the preferred SPS concept resulting from the total SPS exploratory development program?

6. What are the elements of a post-GBED SPS program?

The following critical issues are associated with these questions.

1. Preferred concept definition

2. Performance feasibility

3. Cost feasibility

4. Environmental and societal acceptance

5. Technology requirements

6. Viability of alternate concepts

7. Implementation strategy

8. Natural resource requirements

9. Safety

The subareas (or disciplines) and subissues associated with system definition and planning are as follows.

1. Subarea/discipline

    a. Reference system (subissues 2a to 2f)

    b. Alternate concepts (lasers, thermal conversion, solid state) (subissues 2a, 2b, 2d, and 2e)

    c. Technology impacts (subissues 2a to 2e)

d. Environmental, societal, and comparative assessment impacts (subissue 2e)

e. System analysis and planning (subissues 2e to 2g)

2. Subissues

a. Energy collection and conversion mass and efficiency (subareas 1a to 1c)

b. Power transmission/reception (subareas 1a to 1c)

c. Space transportation (subareas 1a and 1c)

d. Space construction (subareas 1a to 1c)

e. Costs (subareas 1a to 1e)

f. System integration and analysis (subareas 1a and 1e)

g. Post-GBED planning (subarea 1e)

The subissues are elements that contribute to the critical issues and are the basis for specific projects or tasks that can provide technical data for assessment of the critical issues. Subissue 2f (system integration and analysis) deals with essentially all the critical issues using the existing reference system as a point of departure. This project will provide the integration function of synthesizing all GBED activities related to system definition to answer the fundamental question, "What is the preferred SPS concept resulting from the total SPS GBED program?"

Subarea/discipline 1b (alternate concepts) relates to critical issue 6 (viability of alternate concepts). The project on alternate concepts will include definition and assessment of SPS concepts using laser power transmission, thermal energy conversion, solid-state microwave converters, and other concepts or emerging technologies that may be proposed.

Subarea/discipline 1c (technology impacts) concerns technology advances and/or new technical information that could have an impact on system definition. Likewise, subarea/discipline 1d (environmental, societal, and comparative assessment impacts) concerns analysis of new information in these areas to determine system definition modifications and/or mitigating strategies where indicated. Subarea/discipline 1e (system analysis and planning) addresses SPS implementation strategy and post-GBED planning.

B. SOLAR ENERGY CONVERSION

The projects, technology areas, and critical issues defined in this section address the state-of-the-art improvements that are necessary in solar energy conversion systems to meet the projected SPS performance, cost, and lifetime goals. Table V-1 summarizes the critical issues in this area. An investigation of the availability of semiconductor resources (i.e., gallium) and the feasibility of large-scale, low-cost recovery techniques from basic ores are projected.

Experimental solar cells and blanket assemblies to be developed and tested will potentially meet SPS performance, weight, and cost requirements as well as prove the adequacy of the concept and technology. Cell, blanket, and concentrator manufacture and integration will be undertaken on a pilot scale to demonstrate cost potentials and to provide test hardware for other SPS project areas.

Critical or key questions will be addressed that answer such unknowns as efficiency limits, relative concentration ratio effects, cell degradability and annealability, life expectancy, and reliability for the several solar energy conversion concepts defined. This project also identifies, models, researches, and develops experimental advanced solar energy conversion concepts and technologies that have the potential to improve projected SPS cost and performance goals.

C. ELECTRICAL POWER PROCESSING, DISTRIBUTION, MANAGEMENT, AND ENERGY STORAGE

This section addresses the electrical power processing, distribution, management, and energy storage requirements that will meet the SPS system design goals with reference to performance, cost, and reliability, including a 30-year operational life projection. The challenge facing the power-processor designer is to obtain a low specific mass while maintaining efficiencies above 90 percent and acceptable failure rates over the 30-year operational life of the SPS. The major contributors to power-processor mass are the transformers and inductors necessary for power control. Therefore, the baseline NASA technology is directed toward reducing magnetic component mass through high-frequency (50 kilohertz) operation, heat pipe thermal control, and the development of capacitor/diode voltage multiplier (CDVM) circuitry.

The primary thrust of the GBED program will be the development of multimegawatt power processors, employing scaling relationships, since full-scale demonstration is not possible because of the long leadtime requirement for component development that meets SPS requirements and design goals. Answers to critical and key questions (table V-2) relating to overall system performance while operating in a space environment, which includes attempting to explain and provide workarounds for not so well understood phenomena such as high-voltage/plasma breakdown, plasma and thruster interactions, and spacecraft charging, will be sought in this 5-year GBED effort. Answers to key questions involving power management and energy storage subsystems are also primary subjects of this exploratory development effort, including satellite systems management during eclipse periods.

D. POWER TRANSMISSION AND RECEPTION

The SPS system definition studies to date have been based on microwave power transmission. As a result, considerable depth of penetration of the design and operational issues has been achieved. The key questions that have evolved from the system studies are as follows.

1. Can the required performance be attained for SPS viability?

    a. System efficiency

    b. Focusing and pointing control

    c. RFI

2. Can the required long life and/or maintainability characteristics be achieved?

3. Can manufacturing techniques be devised to provide systems and components of required performance, production rates, and costs?

Table V-3 shows the critical issues and subissues related to these questions. All the performance factors listed under subissues relate to system efficiency and life. As indicated, the performance of both tube and solid-state microwave systems is an issue to be investigated in the GBED effort. The microwave system performance subissue comprises the end-to-end microwave system and thus involves the demonstration of overall performance (efficiency) of the system as a key goal of the GBED effort. An overall dc-to-dc transmission efficiency goal of 55 percent (under laboratory conditions) has been established for the GBED program. Also involved in this subissue is the determination of RFI characteristics and effects for DOE environmental impact studies.

Phase control system performance investigations relate to the critical issue of beam forming and pointing. The transmitting antenna and rectenna element subissues involve performance considerations determined by materials properties (e.g., coefficient of thermal expansion), manufacturing tolerances, alinement, and component efficiencies.

E. STRUCTURES/CONTROLS AND MATERIALS

The key questions to be explored in the structures/controls and materials area are as follows.

1. Can appropriate control strategies and systems be devised for very large, lightweight, flexible systems consisting of several elements of greatly differing natural frequencies and inertias?

    a. Structural-thermal interaction

    b. 1-arc-minute pointing accuracy for a large (1 kilometer diameter) structure of high inertia and long response times

    c. Dynamic isolation of the differing elements (antenna-array)

    d. Control during construction phase

2. Can a composite structural material and other materials for solar reflectors and thermal coatings be developed/demonstrated that

meet the SPS requirements for automated fabrication and indefinite space life?

a. Ultraviolet (uv) and particle radiation effects

b. Outgassing

c. Dimensional stability

Table V-4 lists the critical issues and subissues related to these questions. Projects corresponding to the subissues involve extensive computer analysis and simulations of SPS structural dynamic characteristics and control system performance. The projects also include subscale tests of structural components and major assemblies under simulated environmental conditions for verification of analytical (computer) results. With respect to materials, the critical issues are factors that tend to reduce material functional lifetime; therefore, projects in this area involve selection, fabrication, and accelerated life testing of candidate material samples. A significant research item in this area is the definition of a realistic environmental model (i.e.; uv, particle radiation).

F. SPACE OPERATIONS

The space operations area includes three subareas: (1) automated construction, (2) operations and support functions, and (3) hardware/material handling and installation. The key question in this area is, "Can an SPS-type system be constructed in space in an economically acceptable timespan considering such factors as automated fabrication and assembly techniques; subsystem/structure assembly techniques, including checkout and maintenance; docking/berthing of large masses; and large-scale in-space logistics?"

The critical issues involved in space operations include construction rate/productivity and cost factors, worker safety, equipment requirements, and maintenance considerations. The space operations subissues are as follows.

1. Operations and functions (subarea 2)

2. Automation (subarea 1)

3. Berthing and docking of large masses (subarea 1)

4. Quality assurance (subareas 1 to 3)

5. Logistics (subareas 2 and 3)

6. Hardware/material handling and installation (subarea 3)

7. Packaging (subarea 3)

The projects for each subissue involve design, fabrication, and testing of prototype and/or subscale components or equipment items.

In general, testing will be accomplished in existing zero-g and vacuum test facilities. The construction support activity will involve computer modeling and analysis of large-structure dynamics and subsequent definition methods for transporting, positioning, alining, and attaching major elements during construction operations.

Subissues in the hardware/material handling and installation area involve investigation of packaging concepts and installation/attachment techniques at the component level. The objectives in this area are to demonstrate and assess handling and installation capabilities in construction and maintenance operations.

G. SPACE TRANSPORTATION

This section of the GBED plan defines the critical issues and technology projects necessary to meet SPS transportation system requirements and goals. The primary issues in the delivery of cargo and personnel to orbit are cost and crew/passenger safety (table V-5).

Associated with the larger question, answers will be sought concerning individual elements and components of each transportation system. High among the questions/issues are (1) reuse/refurbishment, (2) reusable thermostructure and cryogenic insulation, (3) engine (including performance characteristics), (4) environmental impacts, and (5) launch, landing, and recovery operations and propellant management in space. Answers to these technology issues and questions relative to the SPS transportation systems will be sought in the 5- to 6-year GBED effort, and an assessment of the cost impact on the total SPS system will be pursued concurrently.

TABLE V-1.- SOLAR ENERGY CONVERSION ISSUES

Subarea/discipline	Critical issue	Subissue
Photovoltaic energy conversion	Producibility	Recovery of gallium from ore
	High performance (watts per square meter; watts per kilogram)	Thin, high-efficiency cells Lightweight blanket and concentrator High-performance concentrators Interconnects and adhesives
	Low cost (dollars per square meter)	Cell cost and production rates Blanket/concentrator cost and production rates
	Long life	Radiation-resistant cells Cell annealability

C-2

TABLE V-2.- ELECTRICAL POWER PROCESSING, DISTRIBUTION, MANAGEMENT, AND ENERGY STORAGE ISSUES

Subarea/discipline	Critical issue	Subissue
Power processing, distribution, and management	High-voltage/high-current operation and performance	Power processing performance and thermal control Switchgear Rotary joint Power conductors Insulators and standoffs Automatic power management
	Space environmental interactions	Spacecraft charging at GEO High-voltage/plasma breakdown Thruster interactions Plasma interactions
Energy storage	Satellite systems management during eclipse	High-performance secondary batteries Fuel cells/nickel hydrogen batteries/superconducting magnetic materials

TABLE V-3.- POWER TRANSMISSION AND RECEPTION ISSUES

Subarea/discipline	Critical issue	Subissue
Microwave systems	System efficiency and life	dc-rf converter (tube and solid state) Antenna system Rectenna collection and conversion Converter operating temperature Waveguide material and dimensional stability
	Beam forming and pointing	Converter phase control Reference phase distribution Subarray phase control Pilot signal phase Incoming noise Antenna attitude control
	Radiofrequency interference	Noise and harmonics Reflected radiation

TABLE V-4.- STRUCTURES/CONTROLS AND MATERIALS ISSUES

Subarea/discipline	Critical issue	Subissue
Structures/controls Structural dynamics Control system Structural tests	Thermal effects on dimensional stability Array-antenna dynamic interactions Control and sensor concepts and placement Stationkeeping Antenna subarray flatness	Structural dynamics characteristics Control system definition and performance Structural element (beams) mechanical characteristics Damping
Materials Materials life	Radiation susceptibility (uv, particle) Thermal expansion Outgassing	Degradation of mechanical properties Fatigue life Dimensional stability Environmental exposure model

TABLE V-5.- SPACE TRANSPORTATION ISSUES

Subarea/discipline	Critical issue	Subissue
Earth-to-orbit heavy cargo	Thermal protection system/ structures reusability	Reusable surface insulation survivability/ refurbishment Honeycomb bonding concepts Composite structures characteristics
	Propulsion systems	Feasibility demonstration of hydrocarbon engines Fuel availability, cost, and combustion products
Earth-to-orbit personnel/ priority cargo	Ballistic recovery of liquid stages	Structures/cryoinsulation reusability
Orbit-to-orbit cargo	Electric propulsion	Electric propulsion performance Long-life operations development
	Man/machine refurbishment operations	On-orbit maintenance concept demonstration
	On-orbit cryogenic propellant transfer	On-orbit propellant transfer feasibility demonstration (zero NPSP[a] pumps; development of pressure/temperature control and liquid/gas separation)

[a]NPSP = net positive suction pressure.

VI. CONCLUSIONS AND REMAINING ISSUES

This section is limited to system-level conclusions of the system definition effort; those conclusions that deal with a specific area, such as power conversion, are treated in that section. The principal overall conclusions are as follows.

A. The reference SPS is a feasible baseload source of electrical power by virtue of nearly continuous illumination in GEO, minimal disturbance of the microwave beam by weather, and an absence of identified insurmountable obstacles.

B. Within the assumed guidelines, the maximum power delivered to the grid by each microwave link is 5 gigawatts. If solid-state amplifiers are used, the maximum is 2.5 gigawatts.

C. Minimum cost per kilowatt is achieved at the maximum output of 5 gigawatts.

Major unresolved issues include the following.

A. The maximum allowable power density in the ionosphere must be defined. This limit determines the maximum power transmitted by each microwave link.

B. Laser power transmission appears to have substantial mass penalties relative to microwave systems, as well as other disadvantages, but has not been defined in sufficient detail to warrant a final judgment.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, June 3, 1981
953-36-00-00-72

APPENDIX - SPS SIZING ANALYSIS

The long-range transfer of power from the solar power satellite (SPS) at geosynchronous orbit to a receiving station on Earth employs the principles of free-space propagation of electromagnetic waves. Narrow beams are more familiar in terms of light sources than in terms of radio-wavelength sources. With large-aperture radiofrequency (rf) sources, however, narrow beams can be created.

Effective production of a narrow beam requires production of coherent planar wave fronts at the transmitter aperture. If this can be done, the properties of the resulting beam are suitable for efficient energy transfer. The field produced by such a transmitter includes a near-field region wherein no appreciable beam divergence occurs and a far-field region with beam divergence. For SPS transmitters of practical interest, the beam will have far-field characteristics at Earth. (See fig. A-1.) The applicable aperture theory shows that, for an ideal antenna (no errors in producing the desired wave front), the product of areas of the transmitting and receiving apertures is a constant

$$A_T A_R = \left(\frac{\pi H K \lambda}{2}\right)^2$$

where A_T = area of transmitting aperture

A_R = area of receiving aperture

H = range; i.e., 37×10^6 meters

λ = wavelength; i.e., 0.1224 meter at 2450 megahertz

The value K is a constant depending on the transmitter illumination pattern as discussed below; it varies from 1.2 to 1.8 for typical SPS transmitters. With $K = 1.5$ and a transmitter area of 10^6 square meters (1 square kilometer), the preceding expression yields $A_R = 114 \times 10^6$ square meters. Thus, the sizes of transmitter and receiver required to effect an efficient energy transfer from geosynchronous orbit to Earth are large but not beyond engineering techniques now realizable. One can, of course, consider making the transmitter larger and the receiver smaller or vice versa. The correct sizing is a constrained cost optimization problem as discussed later.

The simplest illumination pattern for a transmitter is constant rf power density across the entire aperture. One might imagine this also to be the best, but it is not. Some of the energy transmitted does not fall within the main beam but is scattered into rings of "side lobes." The intensity of these side lobes and the total energy so lost is a function of the illumination pattern. For a constant illumination pattern, 16 percent of the energy is lost and the first side lobe (the ring nearest the main beam) has a peak intensity one-fiftieth of the maximum beam intensity at the center of the beam.

System sizing was investigated by use of a parametric model constructed for that purpose (ref. 14). The parametric model examined characteristics of the system over a range of transmitter sizes and total input electric power with specific constraints applied to the energy density in side lobes. Incorporation of the side-lobe limitations necessitated an iteration loop within the model to select the transmitter antenna power illumination taper.

The transmitter and receiver average-to-peak power intensity ratios are shown in figures A-2 and A-3, respectively. These ratios were determined by numerical integration of antenna patterns for a range of power tapers. The average beam intensity can be determined from the total beam and the beam diameter, and the peak values can then be determined from these curves. Figure A-4 shows the variation of the beam spread factor with power taper. The beam spread factor, in turn, affects the beam diameter at the receiver and therefore the peak beam strength. Figures A-5 and A-6 show thermal power dissipation and beam intensity at the receiver over the range of antenna diameters and input power considered. These curves are used to cross plot the design constraint line on final results such as the cost results shown in figure A-7. It may be seen from figure A-8 that the minimum cost SPS design is essentially bounded by constraints. As would be expected, the minimum unit cost system is the highest power system that can be designed within the constraints. The power level is set by the thermal dissipation and ionosphere beam intensity limits. Side-lobe suppression limits exert considerable influence on the design point selection. Reducing the side-lobe limits results in a greater degree of power taper and therefore a "peakier" antenna pattern. This, in turn, causes the thermal dissipation limit and the peak beam strength limit to converge at a larger transmitter diameter and lower power as shown in figure A-8.

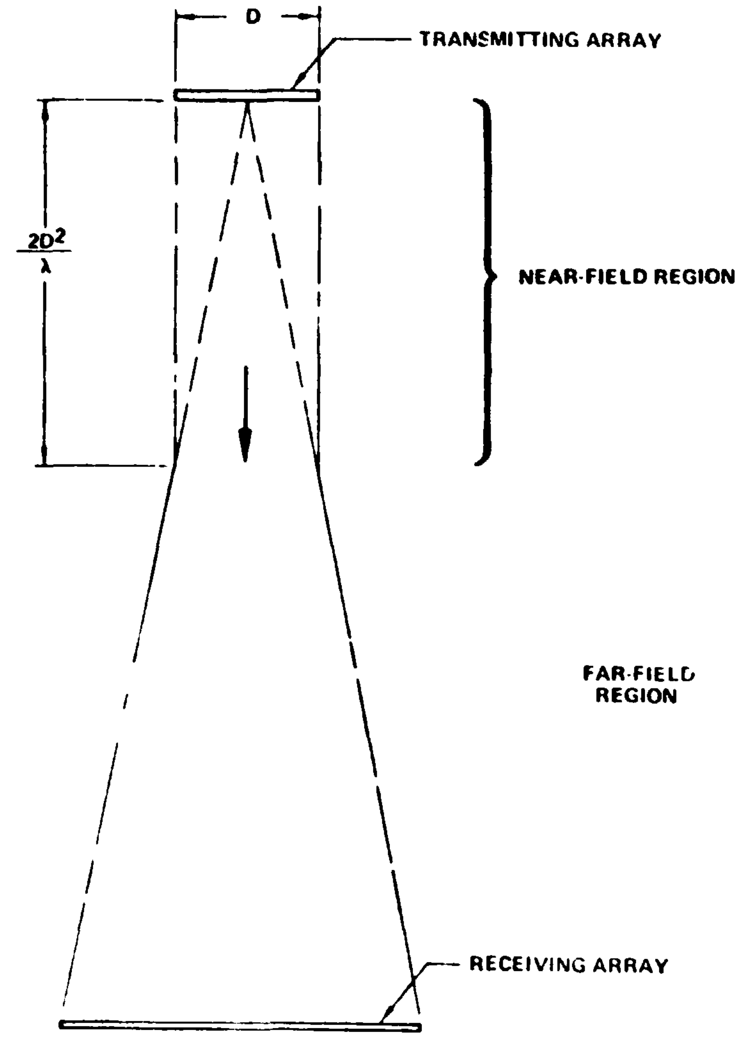


Figure A-1.- Transmitter beam spatial distribution.

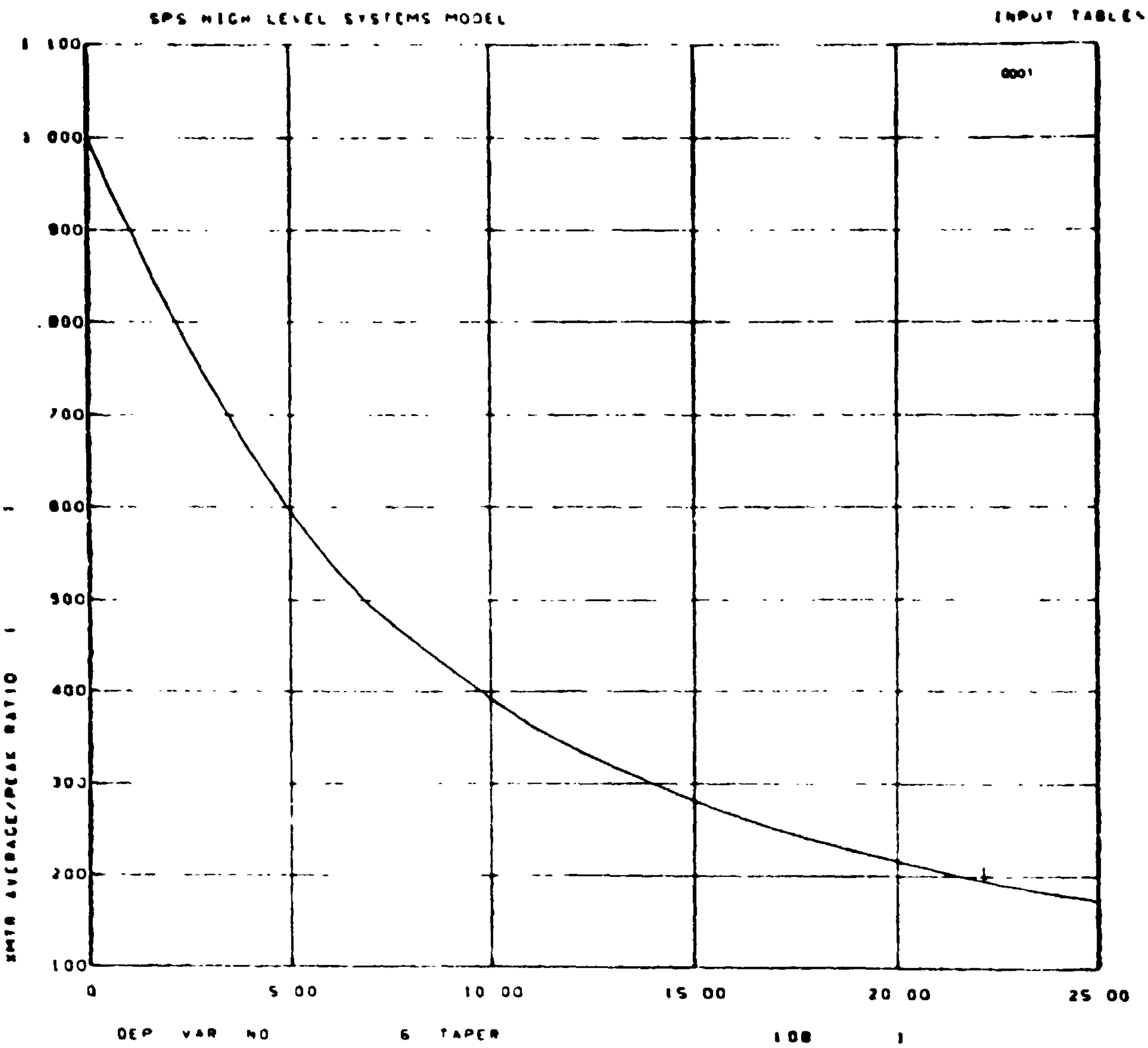


Figure A-2.- Transmitter average-to-peak power ratio.

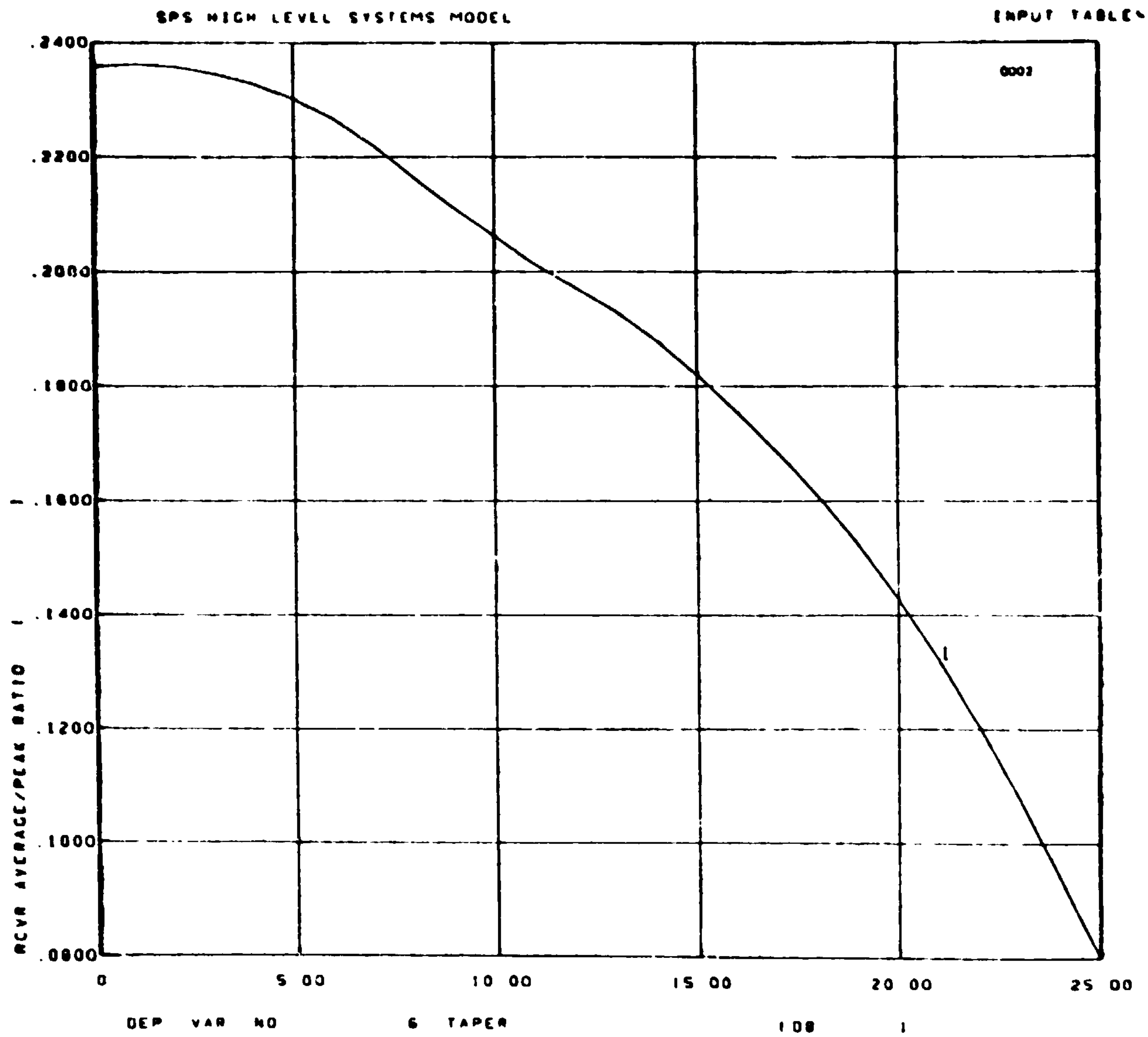


Figure A-3.- Receiver average-to-peak power ratio.

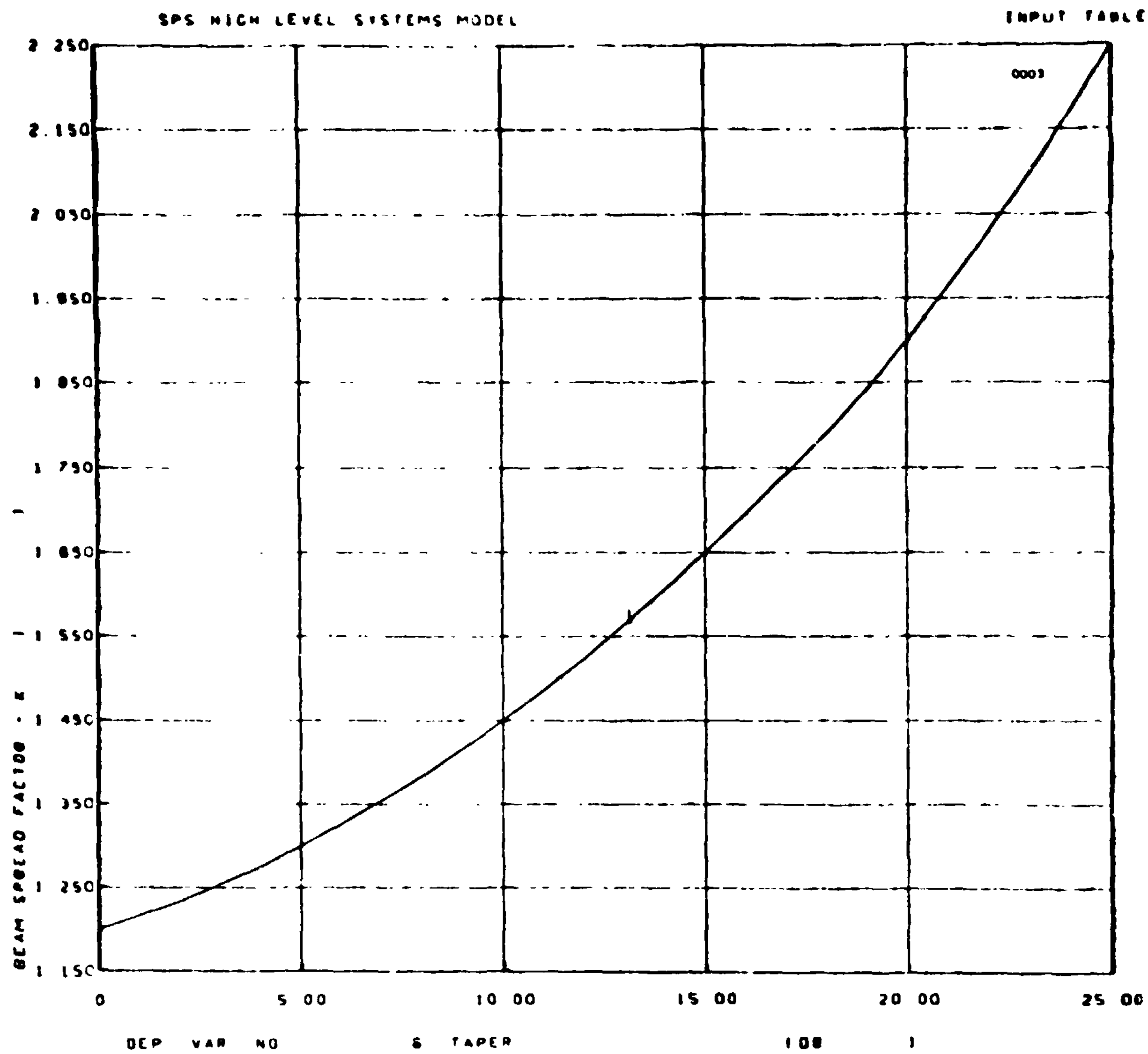


Figure A-4.- Beam spread factor.

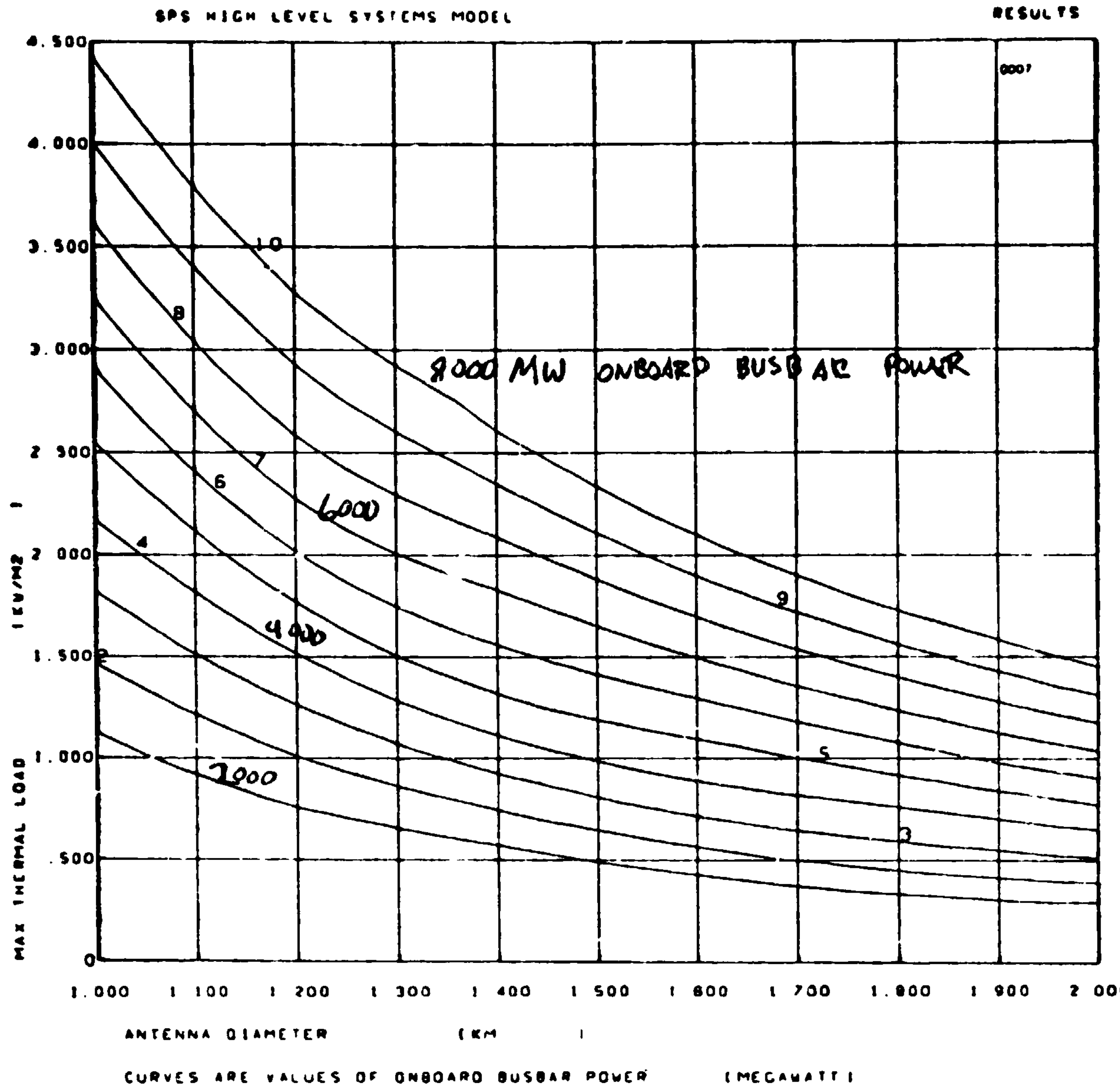


Figure A-5.- Maximum thermal load.

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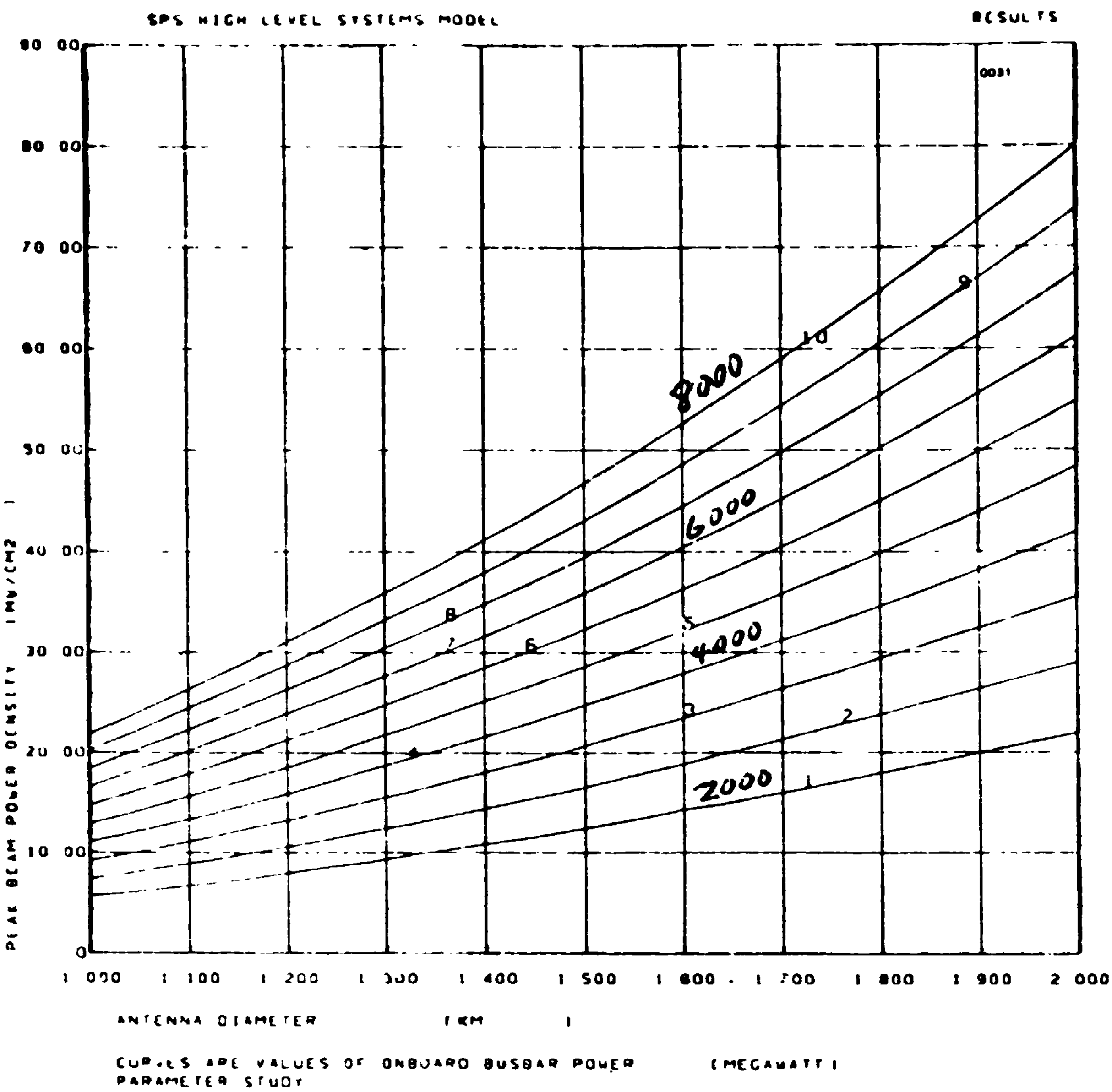

Figure A-6.- Peak beam power density.

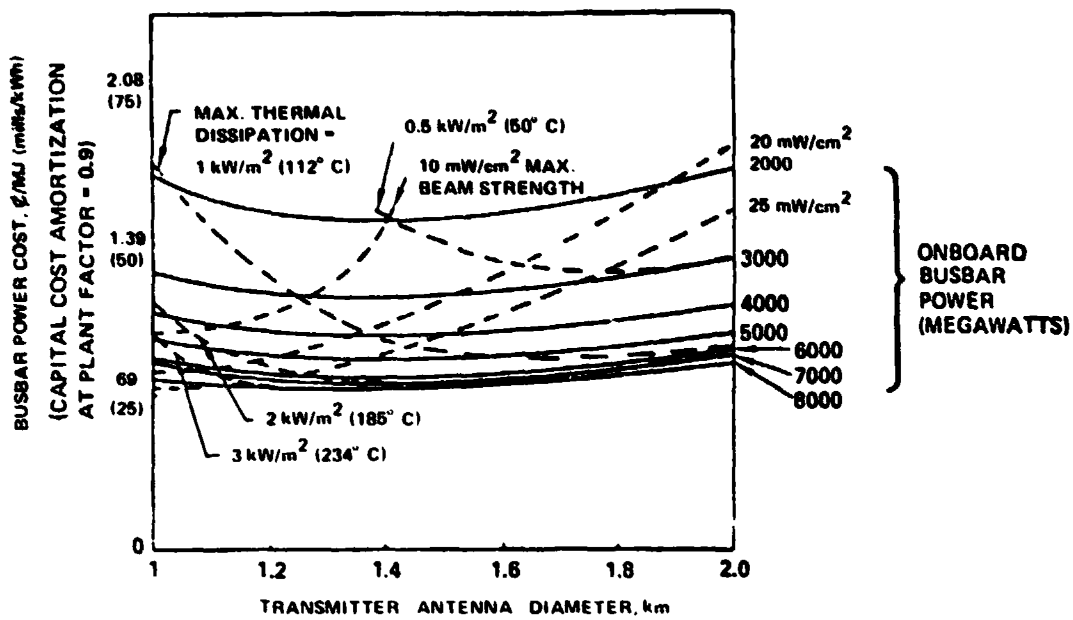

Figure A-7.- SPS system performance with side-lobe limits 100 $\mu W/cm^2$.

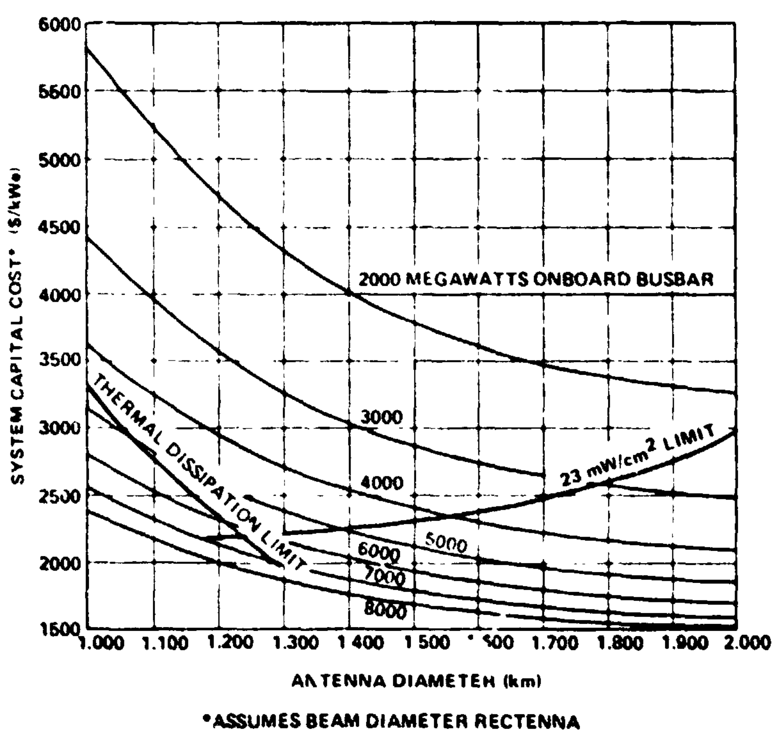

Figure A-8.- Determination of minimum cost design point by transmitter constraints (side-lobe limits set at 10 $\mu W/cm^2$).

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